Master Thesis, Department of Geosciences

Historical Trends in Lake and River Ice Cover in Norway

- *Signs of a changing climate*

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Title: **Historical Trends in Lake and River Ice Cover in Norway – Signs of a changing climate.**

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Front page: Accumulation of frazil ice beneath static ice in Hallingdalselva. Photo taken by Edvigs Kanavin (NVE).

Abstract

Recent studies have shown that the duration of seasonal ice cover on lakes and rivers over the Northern Hemisphere has declined over the 19th and 20th Centuries, mainly as a consequence of rising temperatures. However, lake and river ice trends have not been well documented in Norway. Quality control and homogeneity testing were performed on ice cover data from 48 Norwegian lake and river sites with long records. A total of 142 individual records of ice phenology (freeze-up, break-up and ice cover duration) were evaluated. 23 records were rejected in the quality control or in the subsequent homogeneity testing. The homogenous ice records were analyzed to examine regional and temporal changes in freeze-up, break-up as well as the total duration of ice cover. The full-length records of each site and four different time periods were analyzed: 1913 – 1942, 1954 – 1983, 1982 – 2011 and 1922 – 94. The temporal evolution of trends in ice phenology and hydro-meteorological variables over moving 30-year periods was also examined. The results of trend analyses displayed large variations in both in space and time. The records generally indicated a trend towards later freeze-up, earlier break-up and a decrease in total number of days with ice cover, though few trends were significant at the 5 % level. Freeze-up and break-up was strongly correlated with air temperature and discharge at most sites. The longest record (Mjøsa), covering the 1865 – 2013 displayed significant positive trends in freeze-up and significant negative trends ice cover duration at the 5 % level. The detected rates of change were 1.2 and –1.3 days/decade, respectively. This is similar to the findings of comparable studies from Eurasia and North America.

Key words: Ice cover, ice phenology, freeze-up, break-up, homogeneity, trend, Mann-Kendall, climate change

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Glossary

English	Norwegian
Anchor ice	Bunnis
Autumn turnover	Høstfullsirkulasjon
Black ice/Congelation ice	Stålis
Break up date (BUD)	Dato for isløsning
Break-up	Isløsning
Bulge ice	Svellis
Dynamic break-up	Dynamisk isløsning
Frazil (ice)	Sarr
Freeze up date (FUD)	Dato for islegging
Freeze-up	Islegging
Ice jam	Ispropp
Snow ice	Sørpeis
Spring ice run	Vårisgang
Spring turnover	Vårfullsirkulasjon
Summer stratification	Sommerstagnasjon
Thermal break-up	Termisk isløsning
Winter ice run	Vinterisgang
Winter stratification	Vinterstagnasjon

1 Introduction

1.1 Background

Formation of seasonal ice cover on lakes and rivers is an annual occurrence in alpine, temperate and arctic regions of the world where the winter temperatures average below 0 °C. Ice conditions are a reflection of the meteorological and hydrological conditions, as well as the physiographical (and topographical) extent of the catchment. Meteorological and hydrological conditions will vary both in time and space, with same being true for ice conditions. Hence, changes in the ice cover over time could be an indication of changes in the climate (Assel and Robertson, 1995). As forecasted global warming is anticipated to be largest at high latitudes, continued monitoring of Norwegian ice records can provide an early indicator of predicted global and regional warming. Ice records are especially important because they integrate climatic conditions during the period (autumn-winter-spring) when the most warming is forecast to occur (Duguay et al., 2006).

The geographical position of Norway between the Atlantic Ocean and continent, with a very long coast crossing the Polar circle, results in a winter climate that is highly dependent on polar-front activity. Eastern Norway and inner parts of Northern Norway experience a continental winter climate, with occasional advances of maritime and mild air masses. Western Norway and coastal parts of Northern Norway lie more open to the frequent succession of cold and warm fronts, which brings precipitation and changes in temperature (Devik, 1964). The average winter temperatures over the 1961 – 90 period range from 2.5 °C at westernmost locations of Western Norway to below –15 °C at Finnmarksvidda and in alpine regions of Southern Norway, with the national average being –6.8 °C (eKlima, 2013). Consequently, seasonal ice cover on lakes and rivers is an important part of Norwegian hydrology.

The large variation in temperature is also reflected in the ice conditions. Førland et al. (2007) classified Norway into three ice regimes (Figure 1): (a) a continental ice regime with generally stable ice conditions once the initial ice cover has formed; (b) a maritime ice regime with changeable ice conditions throughout the winter; and (c) an ice regime with seldom ice cover. The latter is typical for a narrow coastal strip of Southern and Western Norway and Trøndelag, but also some deeper low-lying lakes in Eastern Norway.

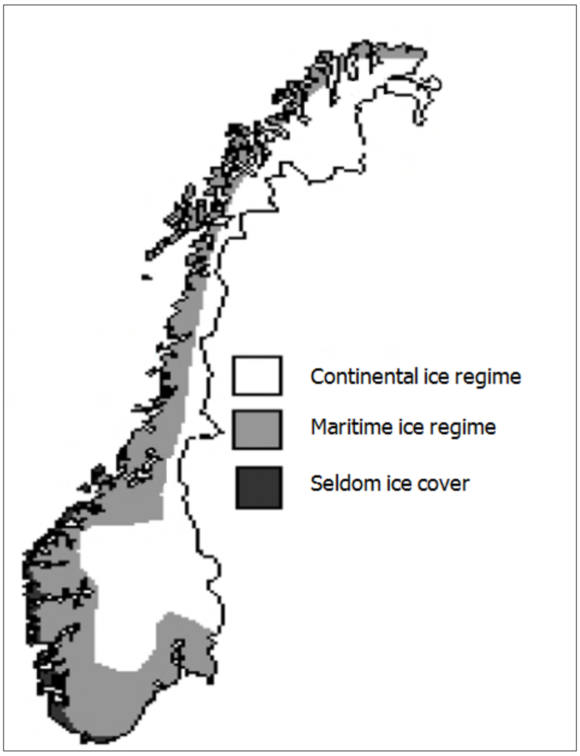


Figure 1: A simplified map showing the three ice regimes. Modified after Førland et al. (2007).

Although the large scale patterns may be regionalized, the ice conditions at specific sites will depend greatly on local factors such as lake depth, exposure to wind and flow velocity (in river). Hence, to compare freeze-up and break-up dates of nearby lakes and rivers, and by that draw conclusions on when the lake or river is usually ice covered, has shown to be difficult. Holmsen (1901) pointed out that the shallow Fiskumvannet (Eastern Norway) is usually ice covered several weeks each winter, while the deep nearby Eikeren is generally free of ice. Ice cover normally forms on the deep Storsjø (2.14) in Eastern Norway during the last week of January. The shallow Lomnessjøen (2.132) a couple of kilometers to the north is usually ice covered from the middle of November.

Human interference in the river basin can lead to significant changes in ice conditions. Given Norway's geography with high mountains, a great number of lakes and rivers and an abundance of precipitation, a large number of hydro-power stations have been constructed. As of 2006, the total number of power stations exceeded 600 (> 1 MW) with a combined installed effect in excess of 28 000 MW and an annual production surpassing 120 TWh (NVE, 2006). Development and regulation of catchments for hydro-power production purposes is an important part of Norwegian hydrology. As a consequence, Norwegian hydrologists have carried out extensive research on how regulations of lakes and river affect the ice conditions, and vice versa (Asvall, 2010).

1.2 Previous work

1.2.1 International studies on trends in ice phenology

Ice phenology (freeze-up and break-up dates and total duration of ice cover) represent an integration of local weather conditions, primarily air temperature. Hence, changes in the average date or duration of an event may reflect changes in the regional climate (Assel and Robertson, 1995). Studies (Robertson et al., 1992; Palecki and Barry, 1986) have shown that freeze-up and break-up dates correlate most strongly with air temperatures in the month or two preceding the event. However, the exact timing of freeze-up and break-up in a given year depends on daily and shorter-than-daily weather conditions such as air temperature and wind speed (Assel and Robertson, 1995). Runoff during freeze-up and break-up will usually also be an important factor in rivers and lakes with substantial through-flow of water (Magnuson et al., 2000).

Numerous studies have been carried out on the subject of historical trends in lake and river ice cover over the past twenty to thirty years. One of the most cited publications, Magnuson et al. (2000), examined ice cover data from major lakes and rivers in the Northern Hemisphere throughout the time period from 1846 to 1995. Twenty-eight sites were included in the analysis each containing more than one hundred years of data. Several European sites were also included in the study (Table 1), though none of them where located in Norway. Three sites in Finland (Tornionjoki River from 1692), Japan (Lake Suwa from 1440) and Russia (Angara River from 1721) commencing before 1800 were also used in the analysis.

Table 1: Linear trends in break-up dates for an excerpt of Finnish lakes and rivers (from Magnuson et al. (2000)).

Site	Period of record	Years of record	Trend (days/100 years)	P-value
Tornionjoki River	1692 – 1995	304	−6.6	<0.001
Vesijävri	1885 – 1995	110	−7.1	0.005
Paijanne	1885 – 1995	108	−8.3	0.002
Kallavesi	1833 – 1995	163	−9.2	<0.001
Näsijärvi	1835 - 1995	161	−8.2	<0.001

The study used linear regression and found significant changes ($p < 0.05$) in freeze-up and/or break-up dates for most sites. Over the 150 year period the average freeze-up for all sites was delayed by 5.8 days per 100 years, whereas the average break-up occurred earlier by 6.5 days per 100 years. The difference between the two was however not found to be significant, as shown by a matched pair t-test. Furthermore the authors found no significant differences between latitudes, continents or between lakes and rivers. A further analysis of the longest records revealed that the trend of reduced ice cover began as early as the 16th century, but that the rate of change was found to be increasing after 1850. Ultimately, the changes in freeze-up and break-up dates were found to translate into increasing air temperatures of about 1.2 °C per 100 years. The study also found evidence of increased inter-annual variability after 1950.

Hodgkins et al. (2002) examined ice data from 29 lakes in the New England-region (USA) with records from 64 to 163 years long. Different from Magnuson et al. (2000), Hodgkins et al. (2002) used the non-parametric Mann-Kendall trend test to evaluate the significance of any trends present in the data (as the trends did not appear linear). The findings were in generally accordance with Magnuson et al. (2000), and results indicated that the break-up dates had become significantly earlier in the entire region, with the greatest change in the southern parts. However, some of the shorter ice records did however not display significant trends. The authors concluded that the change in break-up dates was even more consistent than the air temperature record itself.

Duguay et al. (2006) analyzed spatial patterns of recent trends in freeze and break-up dates across Canada. The time periods used for the study were 1951 – 80, 1961 – 90, 1966 – 95 and 1971 – 2000. A trend toward earlier break-up dates was found for most lakes, while freeze-up dates showed few significant trends. The article further compared the results with trends in autumn and spring 0 °C isotherms over the 1966 – 95 period. Similar trends and patterns as with the freeze and break-up dates was found, i.e. little change in autumn temperatures and large changes in spring temperatures. A strong correlation between the 0 °C isotherm dates and freeze-up/break-up was found at many locations.

Korhonen (2006) analyzed long-term trends in a large number of Finnish lake and river ice records. Twenty of the records commenced prior to 1900, with the Tornionjoki River recorded being the longest. Some of the records included in the study had previously been used by Magnuson et al. (2000). Using linear regression, a trend towards earlier break-up dates was found at several sites. Freeze-up dates displayed few significant trends. The detected trends were statistically significant at most records commencing prior to 1900, while records commencing post-1900 displayed few significant trends. Some exceptions were found in Southern Finland where shorter records showed significant trends. Overall, less than half of the records studied displayed significant trends in either freeze-up or break-up for the observation period prior to 2002.

1.2.2 Norwegian studies on trends in ice phenology

In Norway, few studies have examined patterns and trends in lake and river ice records. Gebre and Alfredsen (2011) suggest that this is because the Norwegian ice records have been relatively inaccessible. The explanation seems reasonable, as most of the old ice observations were only available on paper sheets until recently, when digitized by the Norwegian Water Resources and Energy Directorate (NVE). Over the past decade two studies have examined trends in Norwegian ice records.

Kvambekk and Melvold (2010) examined ice data for the subalpine lake Øvre Heimdalsvatn in southern Norway during the time period 1969 to 2008. Using linear regression, both freeze-up and break-up was found to occur somewhat later in the season, with delays of nine and six days, respectively. However, only the trend in the freeze-up dates was significant at the 5 % level. No significant correlation was found between freeze-up and break-up dates and the air temperature in September and June, respectively.

Gebre and Alfredsen (2011) examined ice cover data for 25 Norwegian lakes and rivers, some of which have also been included in this thesis. The non-parametric Mann-Kendall trend test was used to evaluate the significance of any trends present in the data, while the magnitude of trends was estimated with the robust Theil-Sen slope estimator. Trends in ice phenology (freeze-up and break-up) were attempted explained (correlated) with trends in hydro-meteorological variables such as air temperature, precipitation, discharge and the NAO (North Atlantic Oscillation) large scale teleconnection. The results showed very mixed signals for both freeze-up and break-up trends, perhaps due to the methodology selected for the study. Gebre and Alfredsen (2011) used ice records which had not been quality controlled or tested for homogeneity breaks. Additionally, the authors seemed to be unaware of the fact that several of the sites used had been affected by regulations during the data period, some of which had profound effects on the hydrological conditions.

Furthermore, the study did not make the distinction between partial and complete ice cover. Freeze-up was defined as the first date each winter with ice cover irrespective of which type it was. Such an approach is problematic because it lacks consistency. Finally, the study compared trends in freeze-up and break-up dates at several sites for vastly different time periods. In order to correctly interpret the data, the records examined in a multiple station study should be concurrent, i.e. the observations must cover the same time period (Hirsch et al., 1991). Hence, the results of Gebre and Alfredsen (2011) are not directly comparable to results reached in this thesis, as the before-mentioned points have been dealt with using different approaches.

1.3 Purpose and objectives

Over the past couple of years the Norwegian Water Resources and Energy Directorate (NVE) has digitized a substantial amount of ice records. The data set includes dates for freeze-up and break-up dates of both lake and river sites spread out all over Norway. The earliest ice records commence in the second half of the 19th Century. The quality and homogeneity of the data are uncertain, and thus it is necessary to perform quality analyses and homogeneity tests before the data can be utilized for other purposes, e.g. trend analysis.

High-quality data are essential for all meteorological and hydrological analyses. Erroneous data points and homogeneity breaks can cause apparent changes in long-term meteorological and hydrological time series, which may distort the true climate signal (Tuomenvirta, 2002). As such, an important part of the analysis is to perform thorough quality control and homogeneity assessment of the records before any kind of trend analysis is performed.

The objective of the thesis is two-fold and can be formulated as follows:

- To evaluate the data quality and homogeneity, and select a high quality data set for further analyses.

- To detect potential (regional and single-site) trends in ice phenology and investigate potential causes for the trends observed, including air temperature and discharge.

Further discuss how uncertainty in the data affects the results, and give recommendations for future data collection. The ice record from Mjøsa will studied in detail, as it is the only record with complete metadata for the entire period of observation.

1.4 Outline

This thesis consists of eight parts. A general introduction to the subject of ice records, with a review of previous work and the objectives of the thesis is given in **section 1**. **Section 2** goes into (necessary) detail concerning the theory of ice processes; what governs ice formation, break-up, potential effects of regulation etc. **Section 3** describes the available ice records and hydro-meteorological data which are used in the study, including air temperature and discharge. **Section 4** gives an overview of the methods and procedures used in the quality control, homogeneity testing, trend analyses and correlation analyses. A thorough understanding of the methods is also important to be able evaluate both strengths and weaknesses of the results. The results are contained in **section 5**. **Section 6** discusses the results while **section 7** contains the conclusion. A list of references is given in **Section 8**. A list of the appendices is given **section 9**.

2 Theory on ice formation and break-up

A thorough understanding of the processes of ice formation and break-up, as well as the underlying mechanisms is important to be able evaluate both strengths and weaknesses of the results the trend analyses.

2.1 Physical processes leading up to ice formation

2.1.1 Physical properties of water and ice

Pure water freezes at 0 °C and boils at 100 °C given standard pressure (101.35 kPa). The density of water is temperature dependent, as are many of its properties, but the relationship is not linear. The maximum density of pure water (1000 kg/m^3) occurs at 3.98 °C at normal atmospheric pressure, and it expands and becomes less dense when heated or cooled from this temperature. Although the changes in density are relatively modest over the normal range of water temperature, they have important ramifications. The prime example of this being the turnover of lakes in temperate regions of the world (Dingman, 1984).

In contrast to most substances, water has a lower density in the solid state than the liquid. The density of pure freshwater ice is 916.7 kg/m^3 at 0 °C, whereas water has a density of 999.87 kg/m^3 at the same temperature – approximately a 9 % difference. Like most materials, ice becomes denser with decreasing temperature. However, for practical calculations the density is usually given as 900 kg/m^3 (Asvall, 2010).

2.1.2 Annual circulation patterns of temperate lakes

Lakes in the temperate regions of the world undergo seasonal changes with respect to their temperature and density profiles. The change is caused by variations in the incoming radiation of the sun, which controls the water temperature. Temperature conditions in most Norwegian lakes can be divided into four characteristic periods (which occur over the course of the year).

- Spring turnover (isothermal temperature conditions in entire water column)
- Summer stratification
- Autumn turnover (isothermal temperature conditions in the entire water column)

- Winter stratification

The specific temperature distribution depends on the geographical position (latitude, elevation etc.) of the lake, as well as depth, surface area, through-flow and exposure to wind. Temperature profiles of a typical deep Norwegian lake are shown in Figure 2.

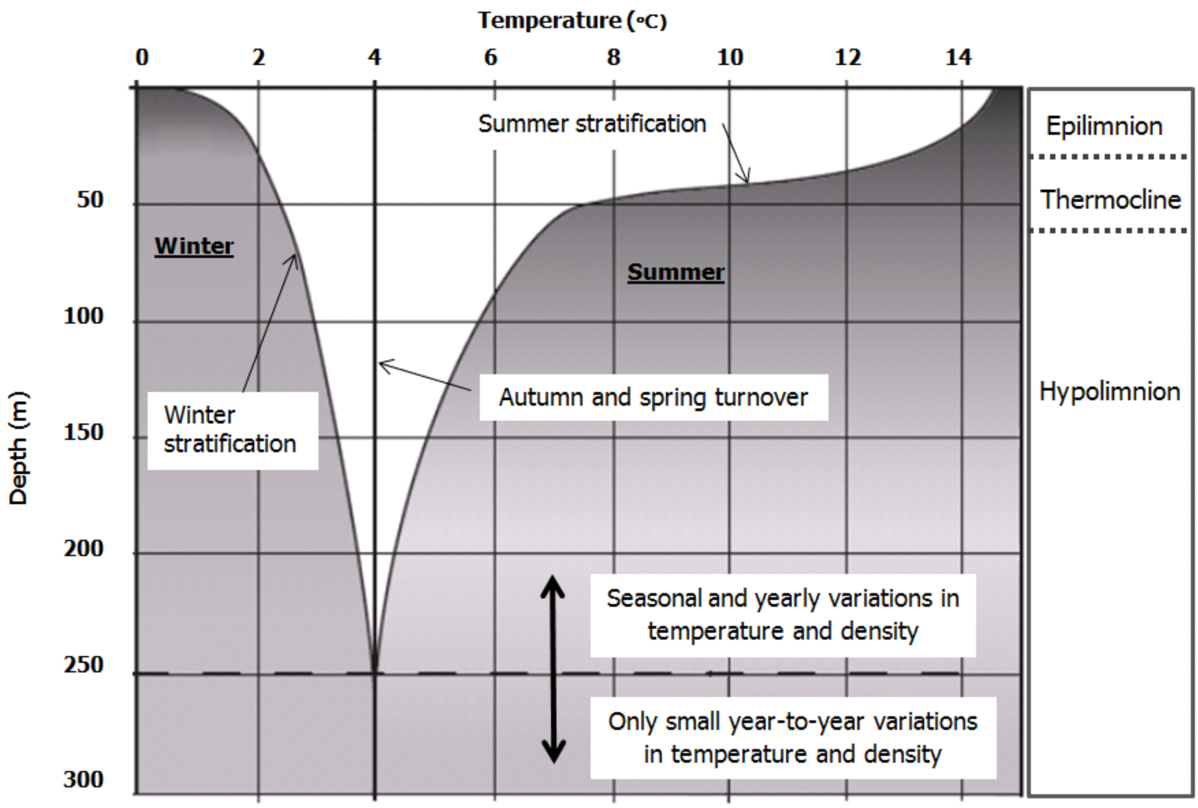


Figure 2: A semi-schematic diagram showing temperature conditions and stratification in (deep) temperate lakes. Modified after Otnes and Ræstad (1978) and Asvall (2010).

The surface temperature of a lake will be close to 0 °C immediately after the ice cover has melted in the spring. At that point, water temperatures will increase with depth, to between 2 and 4 °C at the lake bottom, depending on lake depth and weather conditions before and during the ice formation in the preceding autumn. Once the lake is free of ice, the surface water will be heated, become denser, sink and be replaced by colder lighter water from layers below. This process, which is known as spring turnover, continues until the entire water column has the same density and temperature (~4 °C) (Otnes and Ræstad, 1978).

Additional warming will not result in continued density driven circulation, as the "warm" surface water will be lighter than the colder (denser) underlying water. This leads to the formation of a stable thermal stratification of the lake, with the warmest water on the surface.

The stratification continues and becomes more stable through the summer as the surface water is further heated and the layer increase in thickness. At that point the lake is divided into three characteristic layers, a situation often referred to as summer stratification. The warm surface water layer is called epilimnion, while the colder water layer beneath is called hypolimnion. A relatively sharp temperature gradient (thermocline) is formed in the contact zone between the two layers (Otnes and Ræstad, 1978).

As air temperatures decrease in the late summer/early autumn, the water will eventually start to cool, resulting in (a) density driven circulation. Cooled surface water will sink and be replaced by warmer and lighter water from the layers below. At first, this circulation will only involve the epilimnion and the thermocline, but gradually during autumn and early winter it will eventually also include the hypolimnion. This process, which is known as autumn turnover, continues until the entire water column has the same density and temperature (~4 °C) (Otnes and Ræstad, 1978).

At that point additional cooling will not result in further circulation, as the cold surface water will be lighter than the warmer (denser) underlying water. This leads to formation of a relatively stable thermal stratification of the lake (winter stratification), with the coldest water on the surface. However, the differences in density between the cold surface water and the slightly warmer water beneath are minor. Hence, currents and wind can easily cause mixing of the water to even great depths. Measurements of water temperatures in Storsjø (2.14) during the winter of 1947 – 48 showed the existence of isothermal conditions from the surface to the bottom (300 m) with a water temperature of 2.5 °C (Otnes and Ræstad, 1978).

2.1.3 Heat loss from open water

Heat loss from lakes (and sections of rivers with laminar flow) will result in overturn and formation of thermal stratification, as described in section 2.1.2. Once winter stratification has been established, further cooling will decrease the surface temperature. In the absence of wind mixing, the water temperature will drop to freezing and ice cover will eventually form.

In most rivers, however, the flow is turbulent and vertical mixing will suppress any density (and temperature) stratifications related to the cooling process. Hence, the entire water column will cool at approximately the same rate (Beltaos, 1995). The heat exchange between an open water surface and the air can be described as

$$Q_* = Q_S + Q_L + Q_H + Q_E + Q_P + Q_F + Q_{GW} + Q_B \quad (1)$$

where Q_* is the surface heat flux from water to air, Q_S is the net flux of short-wave radiation, Q_L is the net flux of long-wave radiation, Q_H is the sensible heat-flux, Q_E is the latent heat flux, Q_P is the precipitation heat flux, Q_F is the heat flux to the water from flow friction (conversion of fall energy to heat) Q_{GW} is the groundwater heat flux and $Q_B$is the bed heat flux. With these definitions, Q_* is negative when there is a net loss of energy/heat from the water surface (Dingman et al., 1967).

The short-wave radiation term (Q_S) is controlled by atmospheric conditions (cloud cover, fog), which affect the incoming solar radiation, and by surface albedo, which determines the degree of reflection from the surface. The short-wave radiation is also dependent on solar elevation angle which varies with season and latitude (Beltaos, 1995). The next three terms (Q_L, Q_H, Q_E) are all influenced to various extents by the temperature difference between atmosphere (air) and water. The sensible and latent heat fluxes are also dependent on wind speed (Figure 3). It should be noted that the cooling of river water prior to ice formation is not necessarily a continuous process (Beltaos, 1995). Norwegian weather is typically changeable, and cooling periods are often interrupted by warmer periods where the (Q_L, Q_H, Q_E) fluxes turn positive.

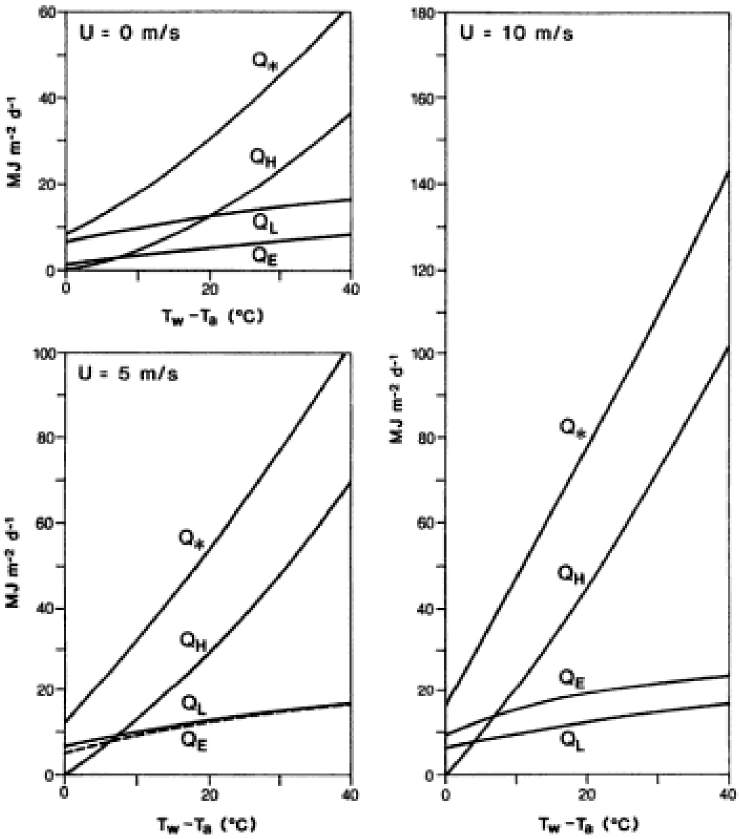


Figure 3: Q_L, Q_H, Q_E and Q_* versus $(T_w - T_a)$ at wind speeds (U) of 0, 5 and 10 m/s with 50 % relative humidity and clear sky conditions. Q_* increases rapidly with wind speed mainly due to increased transfer of heat from the water surface to the atmosphere. The figure is taken from Beltaos (1995) who modified it after Dingman et al. (1967).

The precipitation heat flux (Q_P) can be either positive or negative, depending on the relative temperatures of the river water and precipitate (solid or liquid form). Snow falling into the river will produce the largest heat loss, mainly due to the latent heat which is consumed in melting the snow (heat of fusion >> heat capacity). The three last terms (Q_F, Q_{GW}, Q_B) are generally of less importance compared to the atmospheric terms under open water conditions, but they become increasingly important under ice covered conditions (Beltaos, 1995).

However, for practical applications Equation 1 is generally not used, as energy balance studies are fairly complicated to conduct. Instead, several semi-empirical approaches have been developed (Dingman and Assur, 1969). A pioneer in ice physics was the Norwegian Dr. Olaf Devik who performed extensive experiments on the subject in the 1930s. Through a combination of empirical and theoretical methods, Devik determined the heat loss from a water surface caused by radiation, convection, and evaporation for selected values of cloud cover, wind velocity, and air temperature (Devik, 1964; Asvall, 2010). Today computers make it possible to calculate short term water temperature changes based on standard meteorological measurements like air temperature, air pressure, wind, cloud cover and visibility. An example is the RICE-model (River Ice Model) (Lal and Shen, 1991).

2.2 Ice formation

The processes of ice formation are generally different in still and flowing water, and can be classified as mainly static or mainly dynamic.

2.2.1 Static ice formation

Static ice formation occurs in calm water (mainly lakes) where the flow plays little or no role. Once the surface water has cooled to 0 °C, or slightly lower – some super cooling is necessary, ice formation will occur. When thermal stratification is present, ice will form even though the entire water column has not been cooled to 0 °C. The first ice (crystals) will typically form along the shore, and the ice cover will grow laterally away from the shore in the super cooled surface layer. Static ice formation is the dominant process of ice formation in lake and river stretches with low flow velocity (Otnes and Ræstad, 1978).

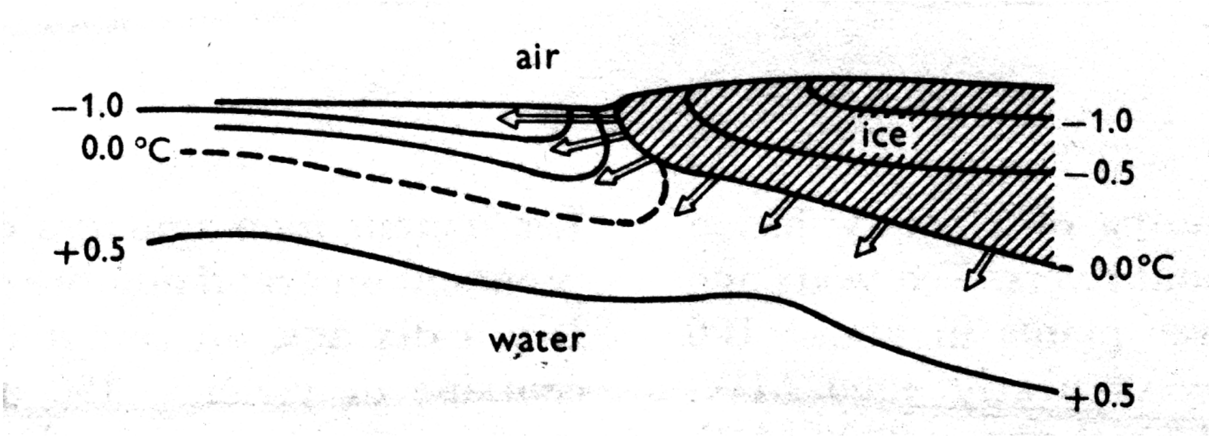


Figure 4: Growth of an ice crystal in super cooled water. Taken from Devik (1964).

2.2.2 Dynamic ice formation

In contrast to still water and laminar flow, turbulent flow will generally result in complete mixing of the water, leading to uniform temperatures in the entire water column. With cooling the water will eventually reach to a temperature of 0 °C. Further heat loss will result in slight super cooling (usually not exceeding 0.1 °C) and small ice particles will form. This form of ice is termed frazil (Beltaos, 1995).

Frazil crystals will grow when the water is super cooled. Mixed with super cooled water frazil have (severe) adhesive properties and is often termed “active”. It can stick to and “coat” other objects within the flow, creating a number of hydro-technical problems, one of the most common being the clogging of intakes to hydroelectric power stations. Once the water temperature reaches 0 °C or more, the frazil loses its adhesive properties and becomes “passive” (Devik, 1964).

Anchor ice is formed in turbulent reaches where active frazil crystals are carried down in the flow and (then) adhere to underwater objects. The continued growth is aided by its rough (“spongy”) surface texture, which acts as trap for other frazil particles passing in the subsurface flow. Anchor ice may form on almost any underwater object, but it most commonly found sticking to aquatic vegetation, boulders, and even large areas of gravel and course sand. Given the right set of hydro-meteorological conditions, anchor ice can grow and thicken to form extensive “blankets” of ice on the river bed (Beltaos, 1995).

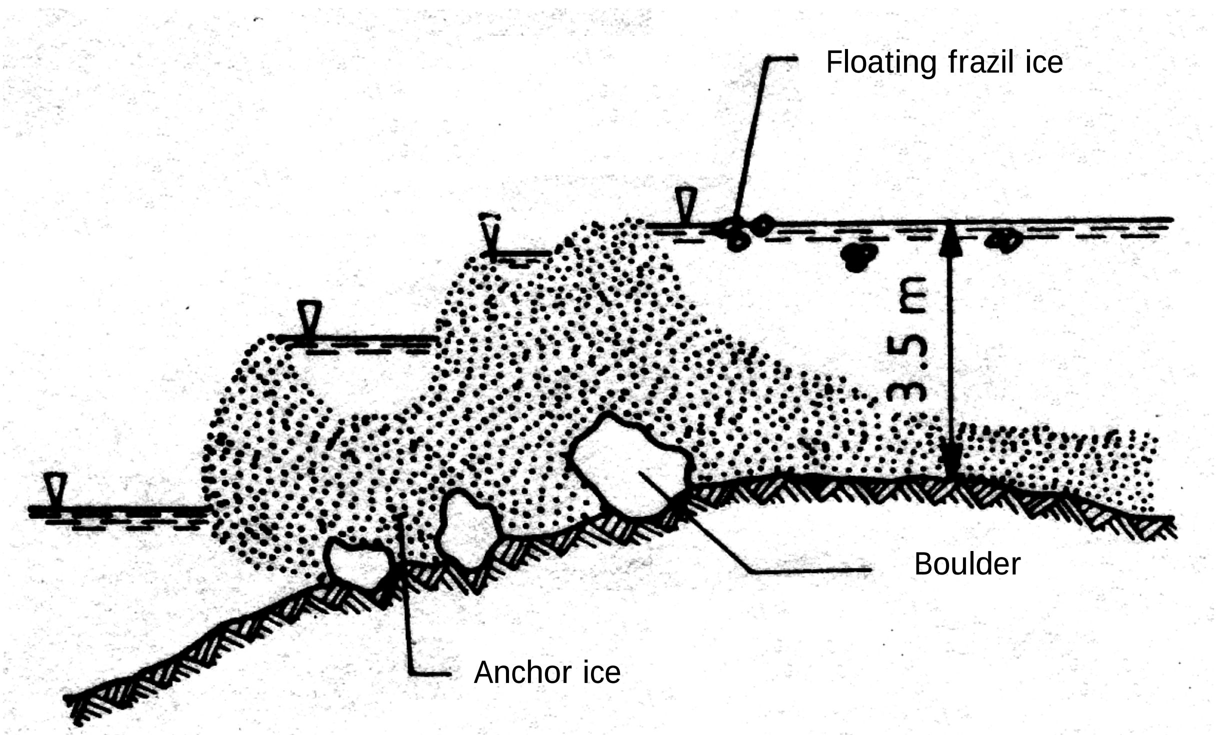


Figure 5: Ice dam in Mistra River, January 1959. Modified after Devik (1964).

In rapids the anchor ice can adhere to boulders etc., accumulate and form dam-like structures (Figure 5), which will increase the upstream water level (and reduce flow velocity). Sections of the river where the flow velocity previously was to high for ice cover formation can then be ice covered. Once an ice cover has formed upstream, super cooling comes to an end and the conversion of fall energy to heat (Q_F) will become increasingly important. Flowing water will heat 1 °C per 427 m of fall, which in many cases is enough to cut through ice dams, causing release of the dammed water and subsequent ice runs downstream. (Asvall, 2010).

2.3 Typical ice conditions in lakes

Ice formation will generally initiate in shallow sheltered areas of the lakes such as coves and inlets. The first ice crystals will typically form along the shore, and (then) grow laterally away from the shore in the super cooled surface layer (Otnes and Ræstad, 1978). Once the initial ice cover has formed, super cooling of surface water comes to an end. Further growth (thickening) of the ice cover is due to freezing of water on the underside of the ice sheet. This will occur when surface air temperatures become low enough to allow the heat of fusion to be conducted upward through the existing ice cover (Beltaos, 1995). The heat loss through the ice cover decreases with increasing ice thickness. Hence, the growth of ice slows down with increasing ice thickness, all other conditions being the same. The process of downward growth of crystals into the water column is called congelation. Ice that forms in this process is called black ice, clear ice or congelation ice. The rate of ice growth is determined by the difference between the heat fluxes at the top and bottom of the ice sheet (Beltaos, 1995). It can be expressed as

$$\frac{dh_i}{dt} = \frac{1}{\rho_i \lambda} \frac{T_m - T_a}{\left(\frac{h_i}{k_i}\right) + \left(\frac{1}{C_a}\right) + (\frac{h_s}{k_s})} - \frac{Q_w}{\rho_i \lambda} \tag{2}$$

where ρ_i is the density of ice, λ is the latent heat of fusion of water (3.34 x 10^5 J/kg); T_m, T_a is the temperature at the ice water interface (for this purpose equal to 0 °C) and the air temperature, respectively; h_s, h_i is snow depth and ice thickness, respectively; k_i, k_s is thermal conductivities of ice (2.22 W/(m °C) at 0 °C) and snow (varying from 0.1 to 0.5 W/(m °C) for snow densities of 150 to 500 kg/m^3); C_a is the surface-to-air heat transfer coefficient for the top layer and Q_w is the water-to-ice heat flux, which could be significant if the water temperature exceeds 0 °C (for example due to inflow of "warm" water). The equation assumes linear temperature variation within the ice sheet (Beltaos, 1995). A simplified approach is usually employed for engineering purposes, the most common being the Stefan's equation (named for Slovene physicist Joseph Stefan):

$$h_i = \kappa \sqrt{D_f} \tag{3}$$

D_f is accumulated freezing degree-days and κ is a coefficient which has a theoretical value of $(2k_i/\rho_i\lambda)^{1/2}$. However, for actual conditions it must be corrected to account for exposure and surface insulation due to snow cover. Empirical values of κ is given in Table 2. It should be noted that Stefan's equation gives highly erroneous results for low values of h_i and/or D_f because the term $1/C_a$ will then be greater than (or comparable to) the term h_i/k_i in equation 3 (Beltaos, 1995).

Table 2: Ice growth coefficient (κ) for use in Stefan's equation (in $mm/°C^{1/2}d^{1/2}$). Taken from Beltaos (1995).

Conditions	κ
Theoretical value	35
Windy lakes with no snow	27
Average lake with snow	17 – 24
Average river with snow	14 – 17
Sheltered small river with rapid flow	7 – 14

During the winter lake ice will eventually become snow covered. Snow – especially fresh dry snow – is a good insulator, which will effectively slow down the growth (thickening of the ice cover) of new ice. In some conditions, snow cover can completely halt the ice growth, even at very low temperatures (Figure 6) (Otnes and Ræstad, 1978).

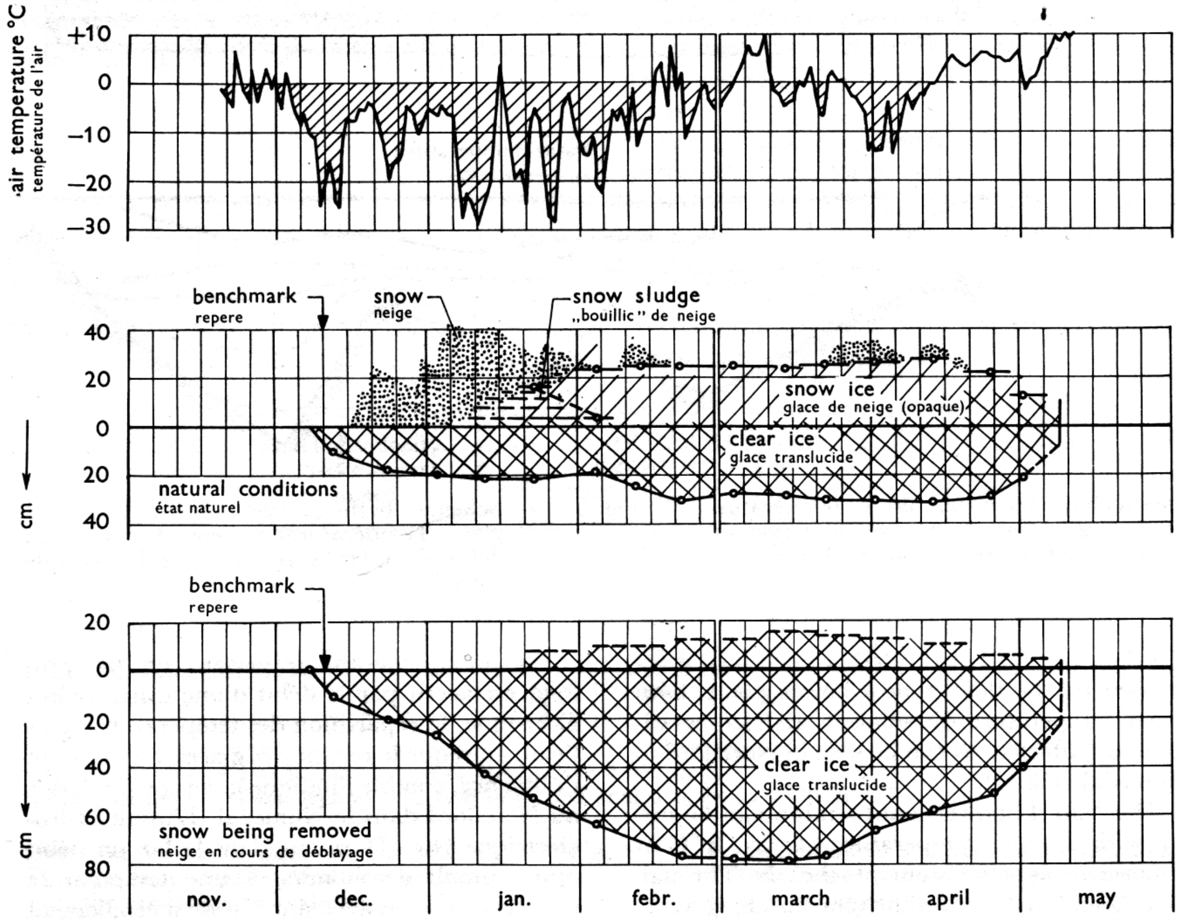


Figure 6: Ice growth on Slidefjord (Norway) during the winter of 1958/59. The middle figure represents natural conditions, while the lower figure represents an area of the lake which was cleared of snow. The effect of snow cover on ice growth is very pronounced. Taken from Devik (1964).

As previously mentioned, the density of pure freshwater ice is 916.7 kg/m^3 at 0 °C, whereas water has a density of 999.87 kg/m^3 at the same temperature – approximately a 9 % difference (Asvall, 2010). If the weight of deposited snow exceeds 9 % of the weight of the ice cover, it will depress the ice. This allows lake water to rise through cracks or holes into the overlying snow cover, which then becomes slush. Capillary action in the snow will lead to additional uptake of water, which will depress the ice further. Snow-slush will freeze and form snow ice in cold weather. Since slush normally freezes from the top down (the cooling occurs from the top), it is not uncommon to find layers (Figure 7) of unfrozen slush sandwiched between black ice and snow ice (Otnes and Ræstad, 1978).

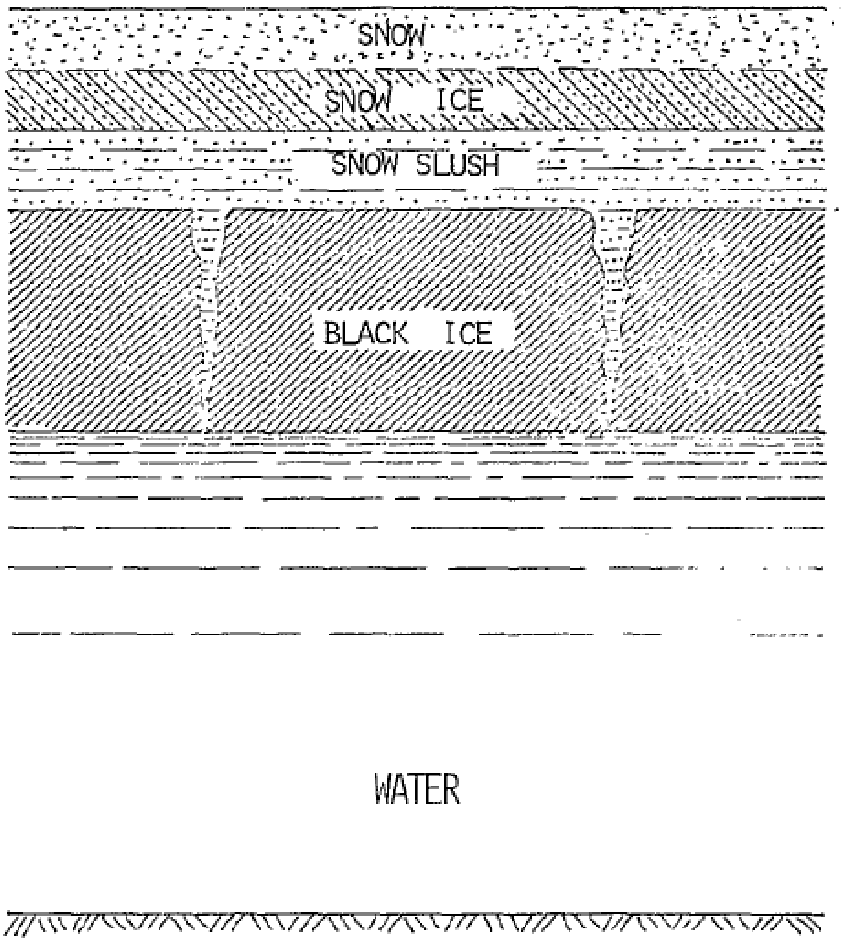


Figure 7: A semi-schematic diagram of a lake with ice cover. Taken from Michel (1972).

In the spring incoming radiation from the sun will increase causing the temperatures to rise. Any snow cover will melt (and/or sublimate) and expose the ice cover beneath. Once the snow is gone, the ice will be eroded from both the top and the bottom. Incoming radiation will penetrate the ice and increase the temperature of the water beneath the ice, causing the ice to melt from the underside. In very shallow lakes, geothermal heat from the lake bottom will also contribute to the ice bottom melting. The inflow to the lake will eventually increase due to melting of snow, leading to increased water levels and the ice sheet will at some point detach from the shore (if it has not happened already – due to melting along the shore). Currents created by winds will further aid the break-up, and cause circulation in ice free areas which will bring up warmer subsurface water to the ice (Otnes and Ræstad, 1978).

2.4 Typical ice conditions in rivers

The process of ice formation in rivers is generally more complex in rivers than that in lakes, and can be characterized as a combination of dynamic and static ice formation, (as) opposed to mostly static ice formation which occurs in still water. Ice formation in rivers is dependent on temperature, flow velocity (discharge) and the geometry and nature of the river channel. Depending on the river reach, ice cover can form as a result of static or dynamic processes. Slow flowing sections with laminar flow will generally have static ice formation, while steeper and faster flowing sections will be ice covered as a result of dynamic ice processes (Otnes and Ræstad, 1978). A transect displaying the different types of ice formation in Glomma (Figure 8) between Barkald and Stai illustrates the complexity of ice formation in rivers.

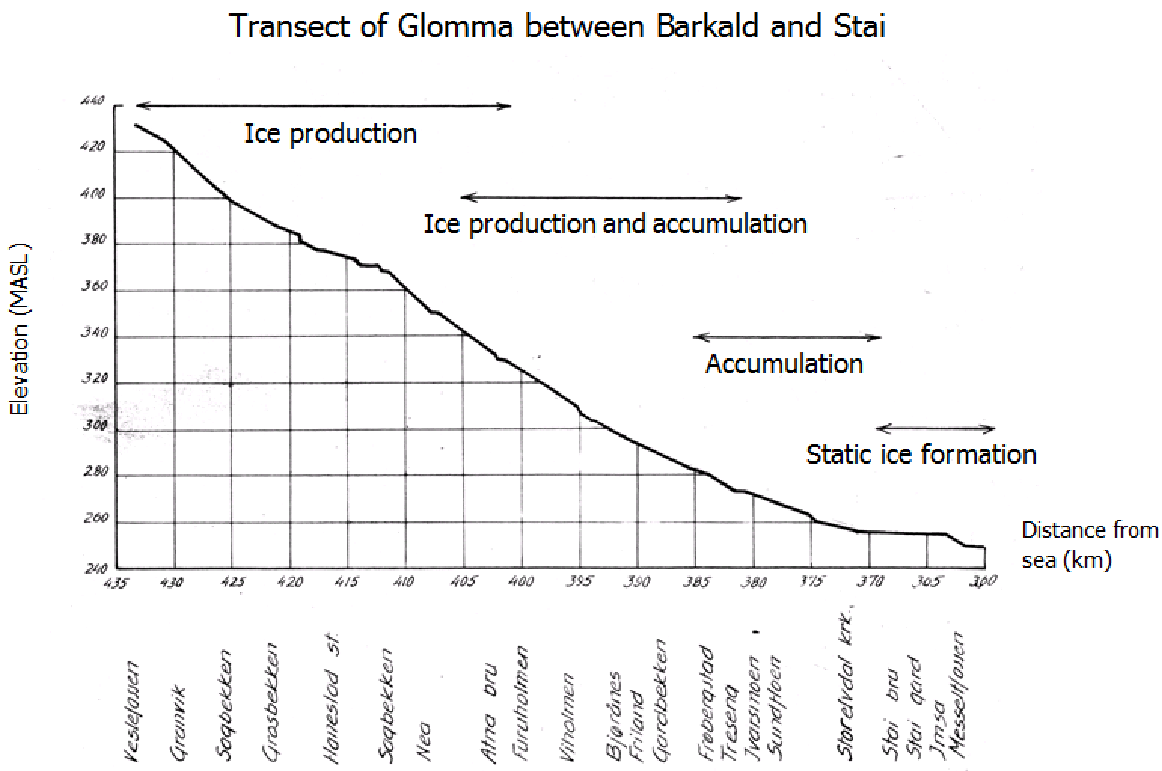


Figure 8: Transect of Glomma between Barkald and Stai. Glomma is Norway's longest and largest river. The river was regulated in 1971/72 at Høyegga upstream Barkald, and a significant share of the discharge was transferred to the neighboring valley Rendalen (and Rena River). The effect of regulation on the ice conditions appears to be relatively minor at Stai (Tvede and Petterson, 1984). Modified after Wold (1965).

2.4.1 Critical water temperature and flow velocity for ice formation

Studies of Norwegian rivers in cold conditions have shown that there is a clear link between ice formation, water temperature and flow velocity (Figure 9). Given a flow velocity of 0.6 m/s, the river will not establish an ice cover even if the water temperature is a low as 0.02 °C (Devik, 1964). The heating of water due to conversion of fall energy is in the order of 1 °C per 427 m of fall. Hence, a waterfall of ~8 m can potentially increase the water temperature by 0.02 °C. This temperature increase might seem insignificant, but it is actually sufficient for cutting through ice dams under ice covered conditions (Fergus et al., 2010).

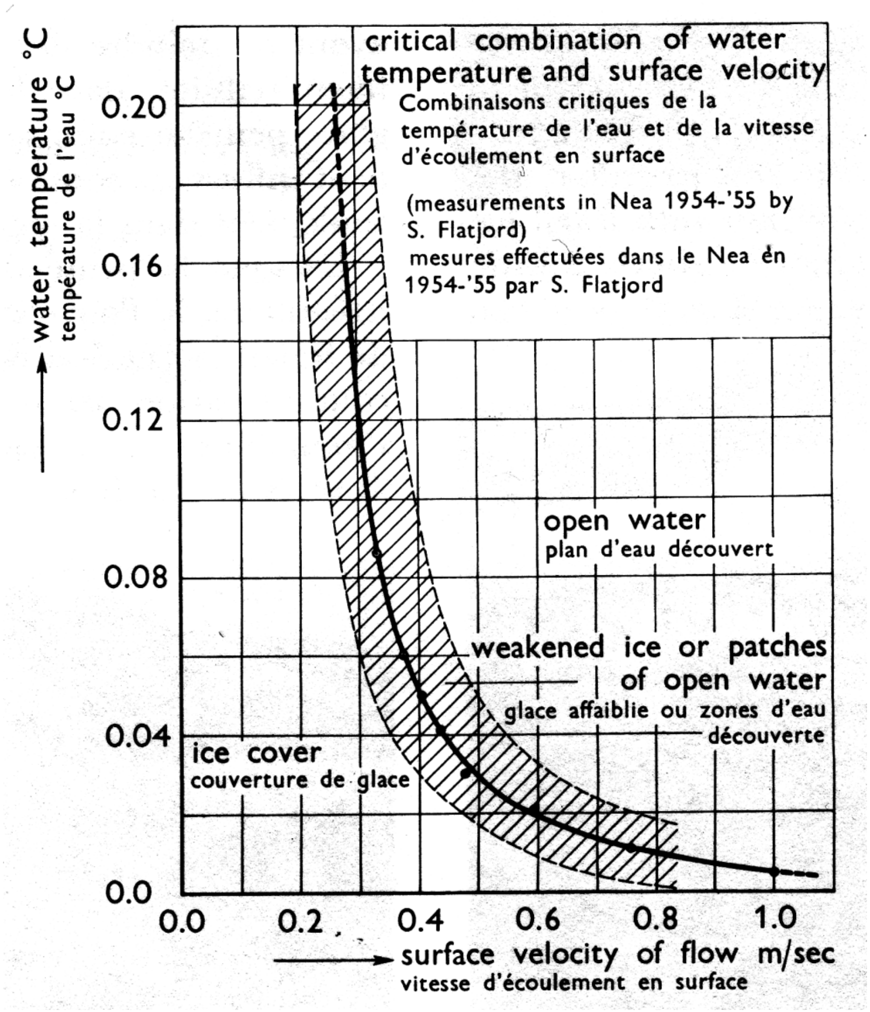


Figure 9: Critical combination of water temperature and surface velocity. The temperatures referred to were measured in "mixed" water (isothermal conditions) at some depth in holes/channels in the ice, not in super cooled surface layer. Taken from Devik (1964).

2.4.2 Ice formation on reaches with low gradients

River reaches with low gradients will have laminar (or near-laminar) flow, making thermal stratification of water possible. Hence, the process of ice formation will generally mimic that of lakes, though it can to some extent be affected by variations in the discharge (Fergus et al., 2010). Ice cover will form through static ice formation at the banks and grow laterally toward the middle of the stream (Figure 4). The lateral growth will occur even when the main water temperatures slightly above freezing (Figure 9), depending on flow velocity and meteorological conditions (Devik, 1964).

Vertical growth (thickening) will occur as in lakes, but frazil produced in upstream rapids will typically also accumulate under the ice and form “hanging dams” (Figure 10; Figure 11; Figure 12). Hanging dams will continue to thicken until the ice supply is depleted, or the constriction they create increase the local flow velocities enough to cause a resumption of ice transport. In some cases, flow velocities may be sufficiently increased to cause localized erosion of the river bed and banks (Beltaos, 1995). Frazil accumulation can lead to extreme variations in ice thicknesses. Measurements of ice thickness in Glomma (Figure 8) show that while the average thickness downstream Stai (static ice formation) is ~0.75 m, the average thickness at Treseng (accumulation of frazil) exceeds two meters (Wold, 1965). Similar results have been reported from other Norwegian rivers (Figure 10).

Figure 10: Accumulation of frazil beneath static ice in Hallingdalselva. Photo taken by Edvigs Kanavin (NVE). Taken from (Beltaos, 1995).

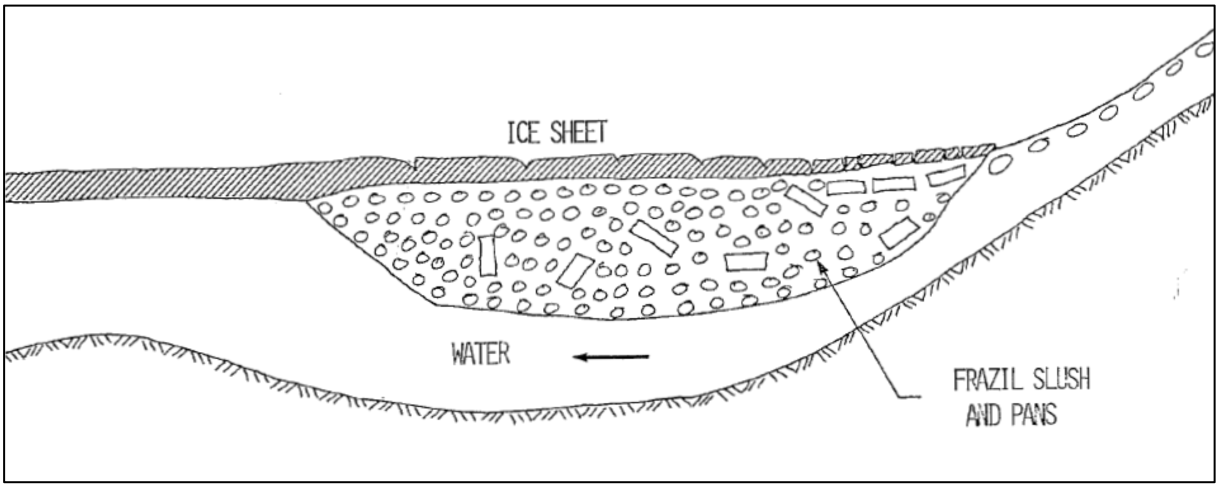


Figure 11: Hanging ice dam seen from the side. Taken from Michel (1972).

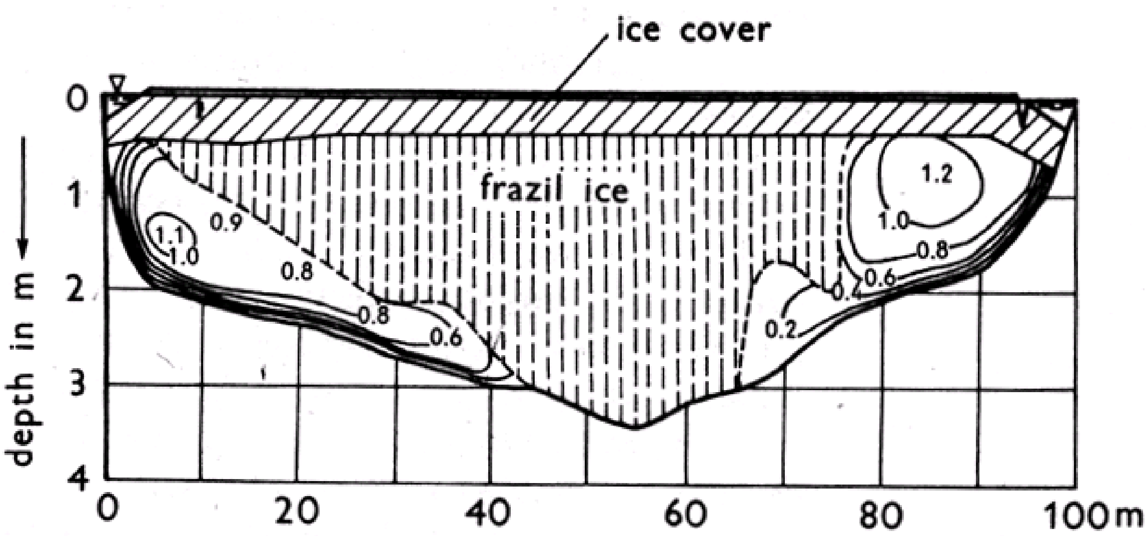


Figure 12: Cross section of the Nea River in January 1955 illustrating a "hanging dam". The total area of the cross section was 230 m^2, of which 160 m^2 (70 %) was blocked by ice. The discharge at the time was 58 m^3/s. Taken from Devik (1964).

2.4.3 Ice formation on reaches with moderate gradients

When the flow velocities are moderate, ice will generally form at the banks and grow laterally. With flow velocities less than 0.6 m/s, frazil will usually float at the water surface and stop against transverse ice cover downstream. Hence, ice cover will progress upstream by accumulated frazil against an already formed ice cover downstream. Frazil ice can also affect the growth of ice from the banks, by accumulating along the outer edge of previously formed bank ice. This will generally occur if the flow velocity is ≤ 0.4 m/s. During cold periods this can lead to complete freeze-up of the river (Otnes and Ræstad, 1978).

2.4.4 Ice formation on reaches with steep gradients

River reaches with steep gradients will have turbulent flow and complete mixing of the water. When the flow velocity exceeds 0.6 – 0.8 m/s, frazil crystals will no longer float at the surface, but instead be mixed with the water and carried down in the flow. In the case of transverse ice cover downstream, frazil will submerge under the ice and accumulate (under the ice) when the flow velocity decreases sufficiently. Some of the frazil will also stick to the river bottom in rapids and lead to build-up of anchor ice and ice dams (Figure 5) (Otnes and Ræstad, 1978).

2.4.5 Break-up of river ice

River ice break-up can be divided into thermal or dynamic break-up, though both processes are present at some location in most rivers (depending on the reach). The type of break-up is generally dependent on meteorological and hydrological conditions (Fergus et al., 2010).

Thermal break-up of river ice is similar to break-up of lake ice. The discharge remains low during the melting phase while thermal processes weaken the ice cover. The ice will eventually detach from the banks and lose significant strength. At that point, a channel will often melt (open) the ice, and the bank ice will broken of piece by piece and floated downstream without causing problems. Contributing factors include solar radiation, wind (erosion) and increased water and/or air temperature. Thermal break-up is usually prevalent in rivers with low spring runoff following small accumulations of winter snow, and the presence of a thin weak ice cover (Asvall, 2010).

In contrast, dynamic break-up (ice run) can often be characterized by the presence of a strong intact ice cover which may still be attached to the banks. The break-up is caused by a significant increase in the discharge, usually due to extensive snow melt brought on by rising temperatures, sometimes in combination with rain. With rising discharge and water level, the forces acting downstream will rupture and dislodge the intact ice sheet, driving it downstream until the resistance is great enough to halt the movement. This is typically a sharp turn of the river, a contraction/narrowing of the channel, human made objects such as a bridge etc., or simply increased friction due to decreased channel slope. The ice will block (jam) the river channel and cause flooding of surrounding areas. Water pressure behind the ice jam will gradually increase, and at some point the jam will give in and be pushed further downstream. In the process, the ice will gradually be crushed into smaller and smaller pieces (Asvall, 2010).

In some rivers ice runs can also occur in the winter due to failure (bursting) of ice dams. The subsequent release of water will increase the downstream discharge, resulting in increased stress on other ice dams, which in turn could also fail, leading to a chain reaction (ice run). As with spring ice runs, the ice and water will continue downstream until the resistance is great enough to halt the movement. The ice masses will block the river channel and cause flooding of surrounding areas. Once a winter ice run has occurred, the river will be cleared of ice and ice formation will take place again. As this occurs in the winter, the ice jam can refreeze and future ice runs will stop against this (at least temporarily – until the pressure is large enough to overcome the ice jam), potentially leading to further flooding and damages (Asvall, 2010).

2.5 Effects of regulations on ice processes

2.5.1 General considerations

Regulation of lakes and rivers for water power purposes can lead to changes in the hydrological conditions. Depending on the type of regulation, both discharge and water temperature could be affected, which in turn can influence ice conditions. The specific effects however, will be determined by what type of water power scheme is constructed. Norwegian hydropower schemes can roughly be divided in two main categories: Hydropower schemes without and with storage capacity (NVE, 2006).

Hydropower schemes without storage capacity are often called “run-of-river power plants”. They are typically found in the lower reaches of rivers where the discharge is high and the hydraulic head relatively low. Given the lack of storage capacity, they will usually have minor influences the discharge or water temperatures of the river. Unless, of course, the water intake is located high up in the mountains. In such cases water temperatures can be greatly affected. (NVE, 2006).

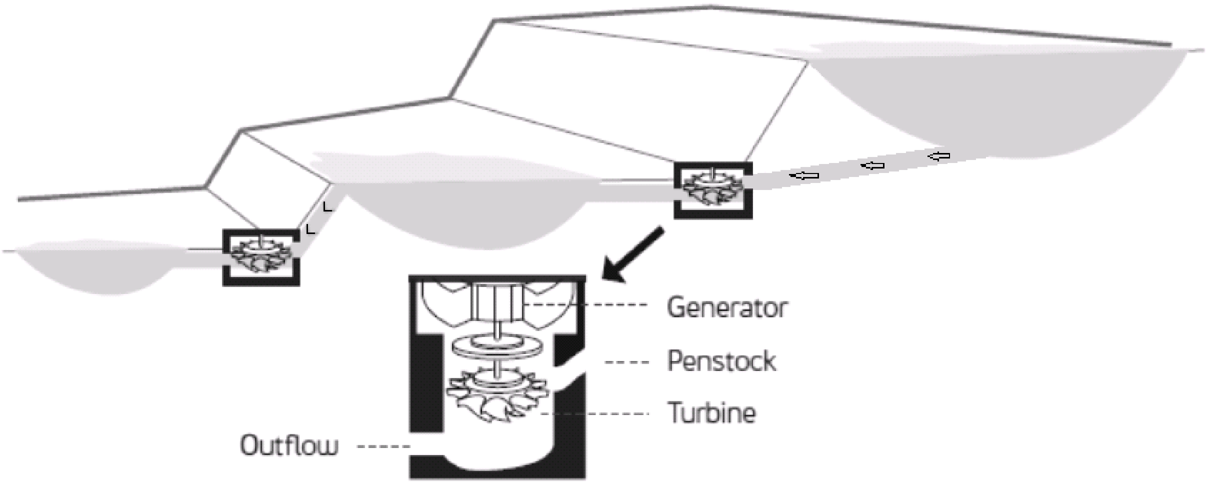


Figure 13: A schematic diagram of a hydropower scheme with several reservoirs and power stations. Modified after Statkraft Energi AS (2009).

Hydropower schemes with storage capacity will usually have reservoirs located in the mountains to give a large hydraulic head. They often consist of several storage schemes, and in some systems a number of power stations are positioned in cascade one after another to maximized the use of water (Figure 13) (NVE, 2006). In contrast to run-of-river schemes, hydropower schemes with reservoirs will affect both discharge (Figure 14) and water temperature of the river downstream (Otnes and Ræstad, 1978).

The typical operation of such schemes is based on storing the spring and summer runoff, which is then released in the following winter(s). Hence, the discharge downstream the power station is generally reduced during the spring and summer, while the winter discharge will increase. The water temperatures downstream will generally decrease in the summer and increase in the winter, as water is withdrawn at some depth in the reservoir and led in base rock tunnels to the power station (Tvede and Petterson, 1984). The discharge of the river between the reservoir and the power plant will generally decrease, and the water temperature in this section of the river will become more dependent on air temperature. Thus, larger fluctuations throughout the year are likely (Otnes and Ræstad, 1978). This effect is also evident in the immediate vicinity (downstream) of "run-of-river" power stations, where the discharge will be reduced.

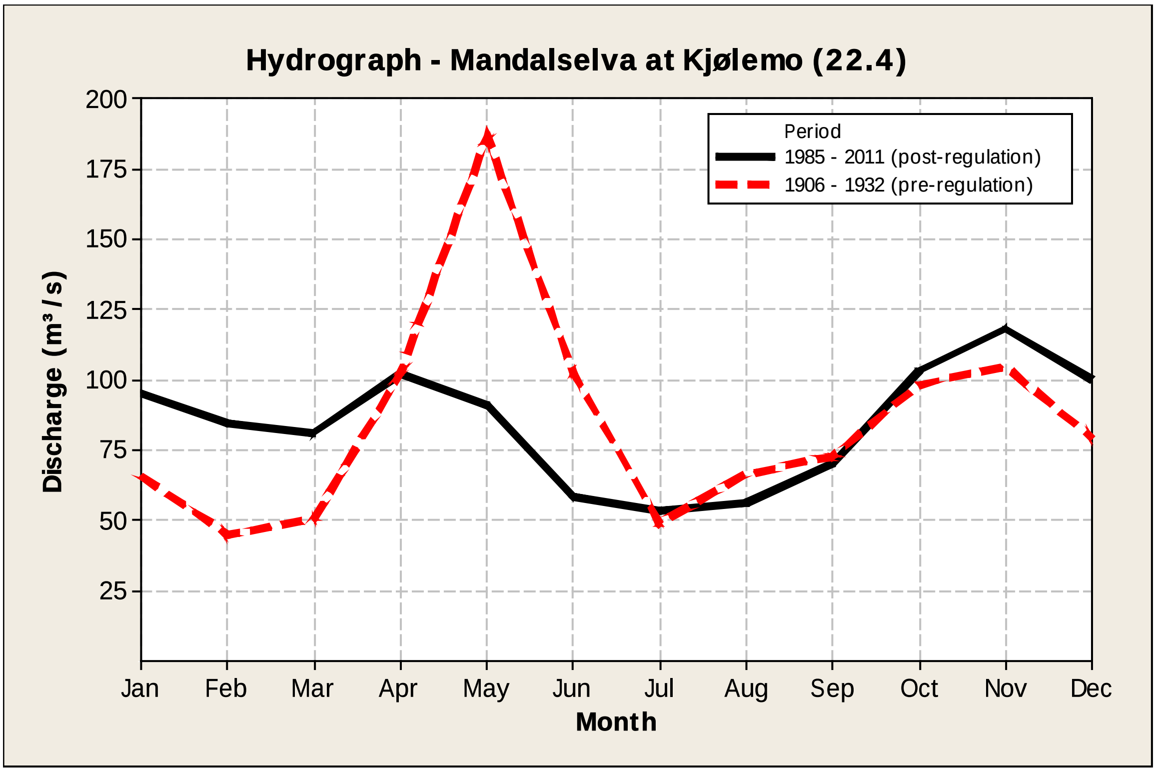


Figure 14: Hydrograph of Mandalselva at Kjølemo (22.4) displaying monthly discharges for pre- and post-regulation conditions. The annual average discharge is approximately the same for both periods (85.5 m^3/s vs. 84.8 m^3/s). The effects of upstream regulations are very pronounced, even though the total regulated volume is only ~15 % (Holmqvist, 2003a). The graph is based on data provided by NVE (Personal communication with Ånund Kvambekk).

2.5.2 Rivers

Reduced discharge will normally lead to decreased stream flow velocity, although the exact amount depends on the hydraulic geometry (Dingman, 1984, p. 241). This in turn will cause more rapid cooling of the water and earlier formation of ice cover. Hence, it will usually result in reduced ice production (frazil) and less ice related problems. However, in the case of wide river channels with low winter discharges, it could lead to complete freeze of the river down to the bottom. This, in combination with groundwater fed bulge ice could cause problems with flooding of areas in proximity of the river. It could also be a potential problem later (in the spring) when the spring flood come if the channel is blocked by ice. However, problems associated with this are generally relatively insignificant, except perhaps in cold winters with limited snow cover (Otnes and Ræstad, 1978).

On river stretches with a relatively large inflow of groundwater, reduced winter discharge could lead to weakened ice coved along the shore. When the natural runoff is reduced, the groundwater, which has a higher water temperature than the natural runoff will increase the water temperature of the river. This phenomenon has been observed in Glomma between Stai and Rena after as much as 60 % of the natural winter runoff was transferred to Rendalen in 1971/72 (Otnes and Ræstad, 1978).

Increased discharge will lead to greater flow velocities, which in turn can delay formation of a stable ice cover (Figure 9). Production of frazil ice will generally intensify in rapids with increased discharge, and ice related problems can therefore become more severe. In some cases the problems with flooding etc. have become so severe that it necessitated construction of additional power plants to direct water away from rapids where the ice production was the greatest. Some regulations will also result in increased water temperatures. Higher water temperatures will lead to less ice production and the river will flow open on longer stretches than before regulation (Otnes and Ræstad, 1978).

2.5.3 Lakes

Effects of *increased through-flow* will depend on the amount of through-flow (discharge) and the water temperature of the through-flow. Increased through-flow of *"warm" water* (0.2 – 4 °C) will usually have relatively minor effects in deep lakes (other than a slightly larger ice free area at the inlet), but may have distinct effects in shallow lakes. In some cases the increased through-flow could lead to an open channel through the lake. Increased though-flow of *"cold" water* (0 – 0.2 °C) are thought to have only minor effects, though some studies indicate that it could lead to earlier ice formation and thicker ice cover (Asvall and Roen, 1974). If the changes in through-flow are only minor, ice conditions will generally be more or less unaffected, and thus mimic those of comparable unregulated lakes (Otnes and Ræstad, 1978).

If the lake itself is *regulated by damming*, it can cause changes in the freeze-up and break-up dates, though changes are generally though to be small (Otnes and Ræstad, 1978). However, if the depth and volume of the lake is significantly increased by regulation, it is likely to result in delayed formation of ice cover, as the lake will take longer to cool and establish winter stratification (Fergus et al., 2010).

2.6 History and purpose of ice observations in Norway

Systematic gathering of information on the ice conditions in Norwegian lakes and river were initiated at same time as permanent observations of water stage commenced. The observer's instructions stipulated that both freeze-up and break-up dates, as well as any dynamic break-ups (ice runs) and ice jams should be entered into the observational log. For rivers the observations referred to the ice conditions in the adjacent part of the river. For lakes the observations referred to the visible part of the lake.

The observations were primarily intended as an "aid" to the hydrologist when performing ice reduction[1] (Figure 15) of water stage data (Otnes and Ræstad, 1978), and not intended for long-term studies. Hence, care was probably not taken to ensure homogeneity in the records, and inhomogeneities are thus likely to be present. Possible causes for homogeneity breaks are (not exhaustive) changes in observers, relocation of the station and changes in guidelines for assessment of ice cover. However, it could also be related to changes in the water course itself (regulation).

[1] The presence of ice will significantly change the hydraulic properties of a river channel. Most Norwegian discharge stations experience (to various extents) a backwater effect during wintertime, leading to artificially increased water stages. The effect is caused by ice blocking the channel and reducing the effective cross-sectional area. The actual water level has to be determined by a hydrologist (known as ice reduction), basing the assessment on air temperature, precipitation and information on the ice conditions. Data from nearby ice-free gauges in the same area will often also serve as useful sources of information (Tvede and Petterson, 1984).

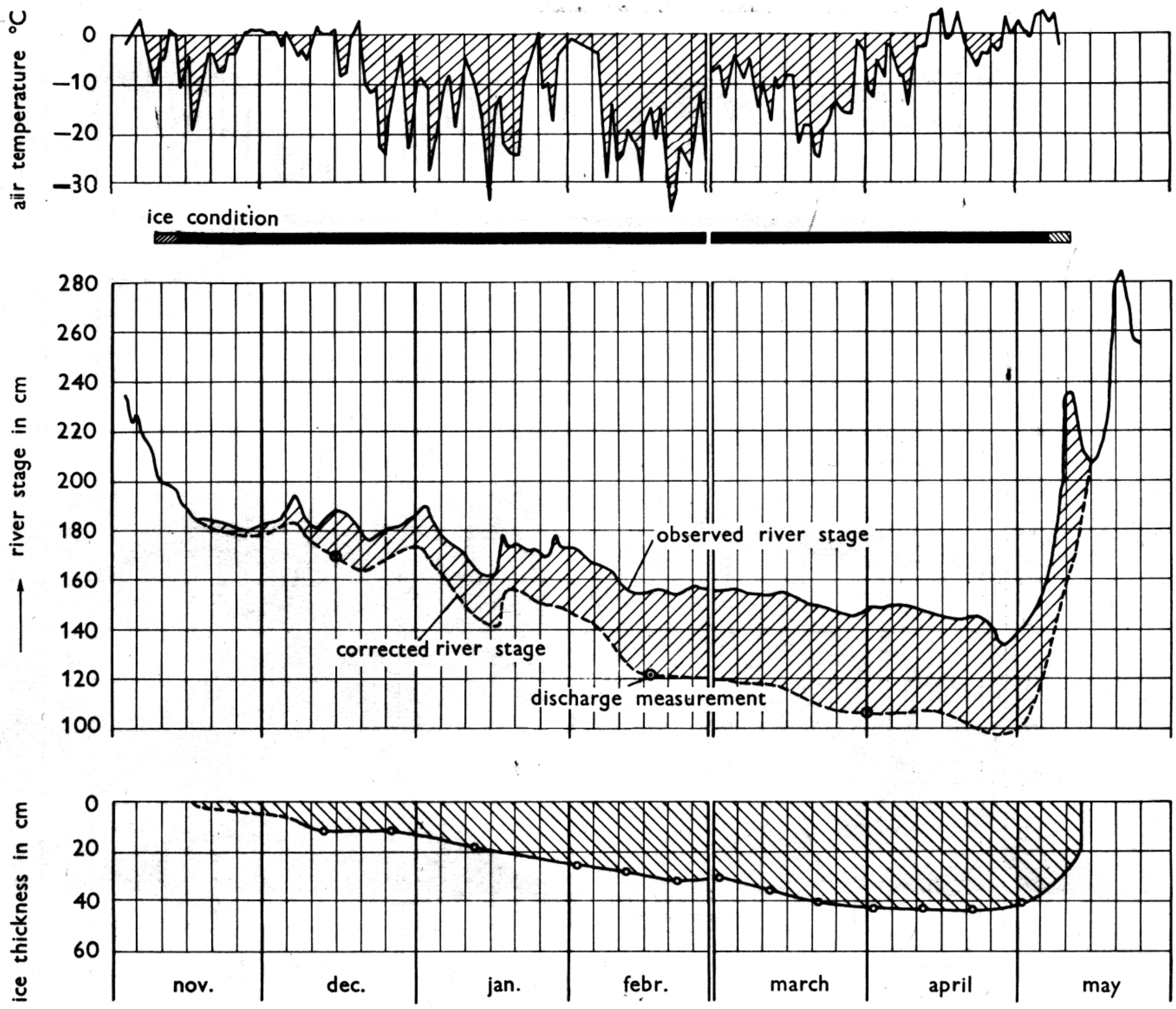


Figure 15: Ice conditions at Nybergsund (311.6) during the winter of 1954/55. The difference between corrected and observed water stages during the period of ice cover is pronounced. Modified after Devik (1964).

3 Data

Access to hydro-meteorological data is generally easy and inexpensive in Norway, even though the meteorological and hydrological services are organized as two separate agencies. The Norwegian Meteorological Institute (met.no) is responsible for issuing weather forecasts, studying climate change and performing meteorological observations. The Norwegian Water Resources and Energy Directorate (NVE) has the national responsibility for hydrology. The directorate performs a variety of tasks ranging from flood warning and flood contingency planning via glaciology investigations to approving applications for construction of hydroelectric power plants. To perform its duties the NVE is dependent on hydrological observations, and as such operates an extensive network of hydrometric stations.

3.1 Meteorological data

Representative meteorological stations for each ice observation site were identified using a two-fold approach. Both distance and climatic resemblance (similar climate) to the ice observation site were emphasized, with decisive weight given to the latter. As the relevant meteorological stations were generally located at some distance to the sites, different microclimatic conditions were likely to exist (at the two). However, as long as the general weather pattern is the same, the analysis should not be negatively affected. Influences of microclimatic effects such as temperature inversions were thought to be minimized by only using monthly data.

3.1.1 Air temperature

Monthly and seasonal meteorological data (mean air temperature) were obtained from the Norwegian Meteorological Institute (met.no). The data were downloaded from eKlima, which is an online database that allows free access for the general public to meteorological data. The database contains daily values for all meteorological stations from 1957 and monthly values for most stations before that. Only temperature data that had been tested (and corrected) and found homogenous, were included in the subsequent analyses of correlation and trend. The homogeneity of the data was assessed by Andresen (2010; 2011). The selected stations are shown in Figure 16.

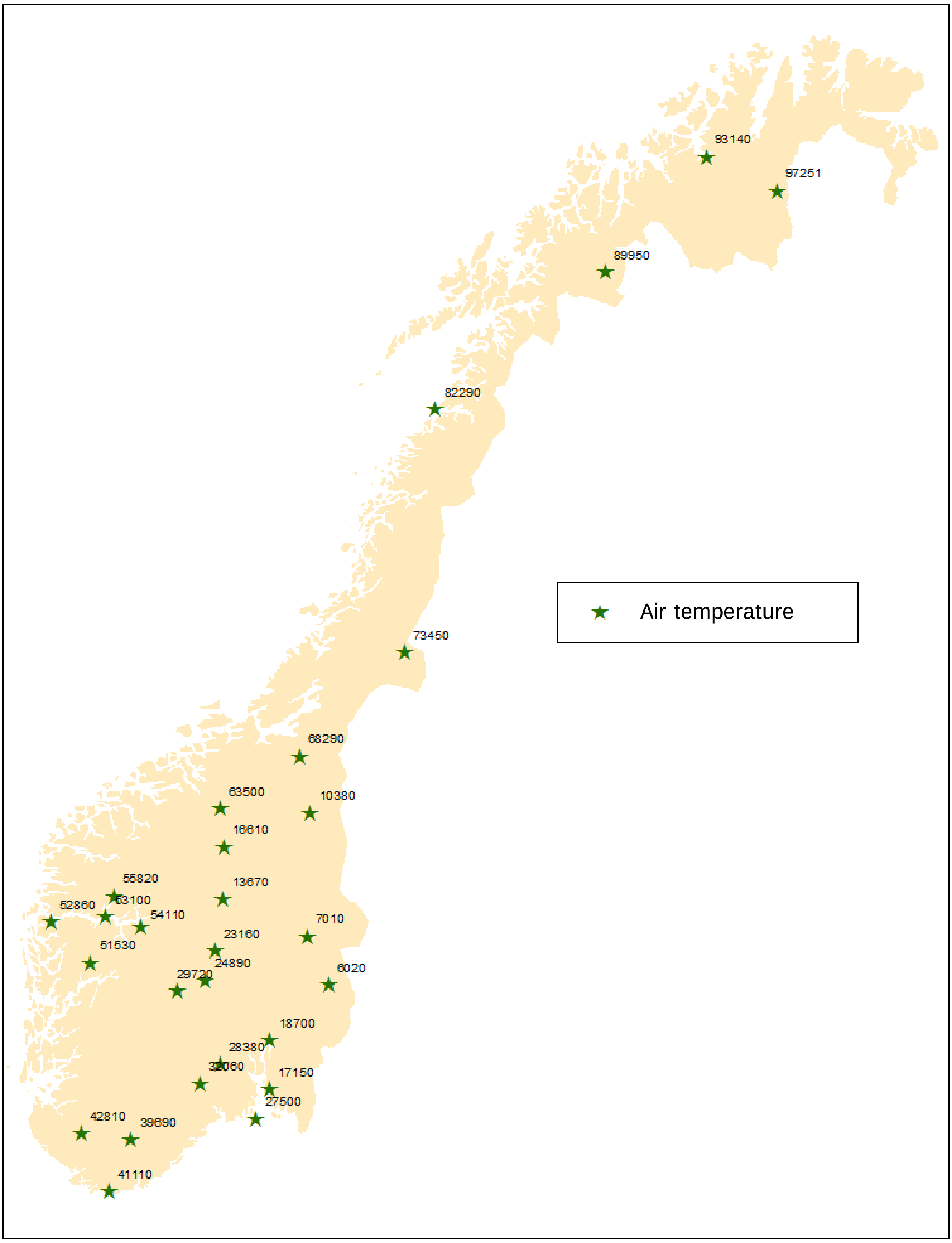


Figure 16: Meteorological stations with monthly air temperature selected for the analyses.

3.2 Hydrological data

3.2.1 Discharge

Monthly ice reduced discharge data were obtained from the NVE. Discharge data were available for all river sites, but some lacked discharge data for the entire period with ice observations. Most of the discharge records had been tested by the NVE for homogeneity breaks at the annual level by Astrup (2000). Detection of inhomogeneities at monthly or seasonal levels was not included in the analyses by Astrup (2000).

3.3 Ice observations

3.3.1 Available data

Observations of freeze- and break-up dates for lakes and rivers were made available by the NVE. The national hydrological database "HYDRA II" operated by the NVE contains over 600 records with at least one year of ice observations. Most records have information on both partial and complete ice cover in addition to ice free conditions. The first observations of ice cover are from the first half of the 19th Century. Mjøsa is the longest continues record[2] with both freeze- and break-up dates available from 1865. Unfortunately, despite the large number of ice records, most are relatively short. Only 65 sites have records longer than 50 years and less than 10 exceed 80 years (Figure 17). Only two sites with more than 80 years of observations are still maintained. Most of the ice observations are from catchments that have been influenced by regulations.

[2] Mjøsa is a composite series. See the discussion for more information.

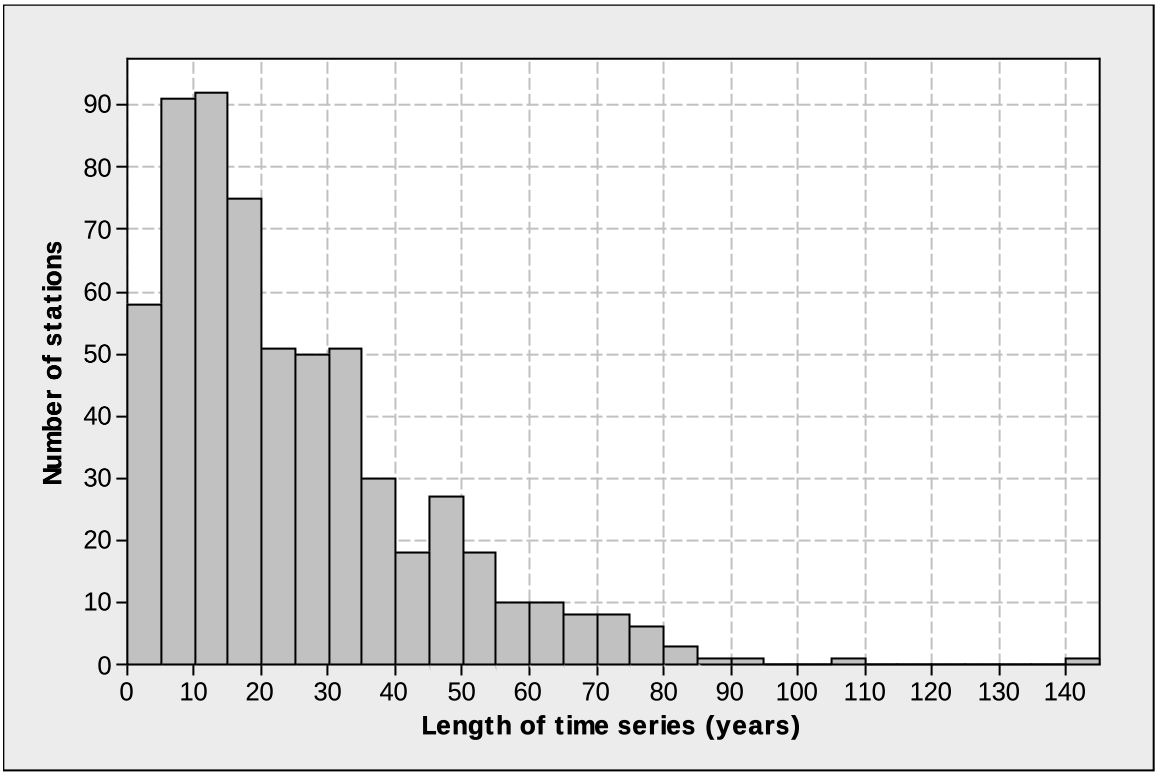


Figure 17: Distribution of ice observation records that are (or previously was) maintained by the NVE and others. The most "up-to-date"-records, with the exception of Mjøsa, are maintained by Glommen og Laagens Brukseierforening (GLB) and reported to NVE. The figure is based on data provided by Ånund S. Kvambekk/NVE.

3.3.2 Selection of sites for the initial analysis

Stations were selected based on the length of the record and the number of missing values. As a general rule only records with more than 40 years of records and less than 15 % of missing values were selected. Some shorter records were included due to lack of long records in certain regions. A total of 48 lake and river sites (Table 3) were chosen for the initial quality control and homogeneity assessment. The spatial and temporal locations of the selected sites are shown in Figure 18 and Figure 19.

Stations were classified based on location (lake or river) and whether or not it was influenced by regulation. A very conservative approach was taken with respect to latter. Some sites (Bulken (Vangsvatnet), Haga bru) were probably only slightly affected (discharge-wise) by regulation (Petterson, 2000; Holmqvist, 2003b), but they were still classified as "regulated". The fact that a station is influenced by regulation does not necessarily mean that the ice conditions have been affected, but for the sake of consistency it was decided to flag the records – at least until the homogeneity assessment had been carried out.

The distribution of the selected sites was not spatially uniform. As shown (Figure 18), the most stations were located in Eastern Norway. Northern Norway accounts for a third of the total Norwegian land area (Statistisk Sentralbyrå, 2012), but only five sites with more than 50 years of ice observations could be found in the region. Only one station (Polmak) had fairly recent observations, ending in 1998. The discrepancy between area and station coverage can probably be explained with population density. The largest population concentrations are located in southern parts of Norway, leading to an overrepresentation of sites as the need for hydrometric observations was larger here.

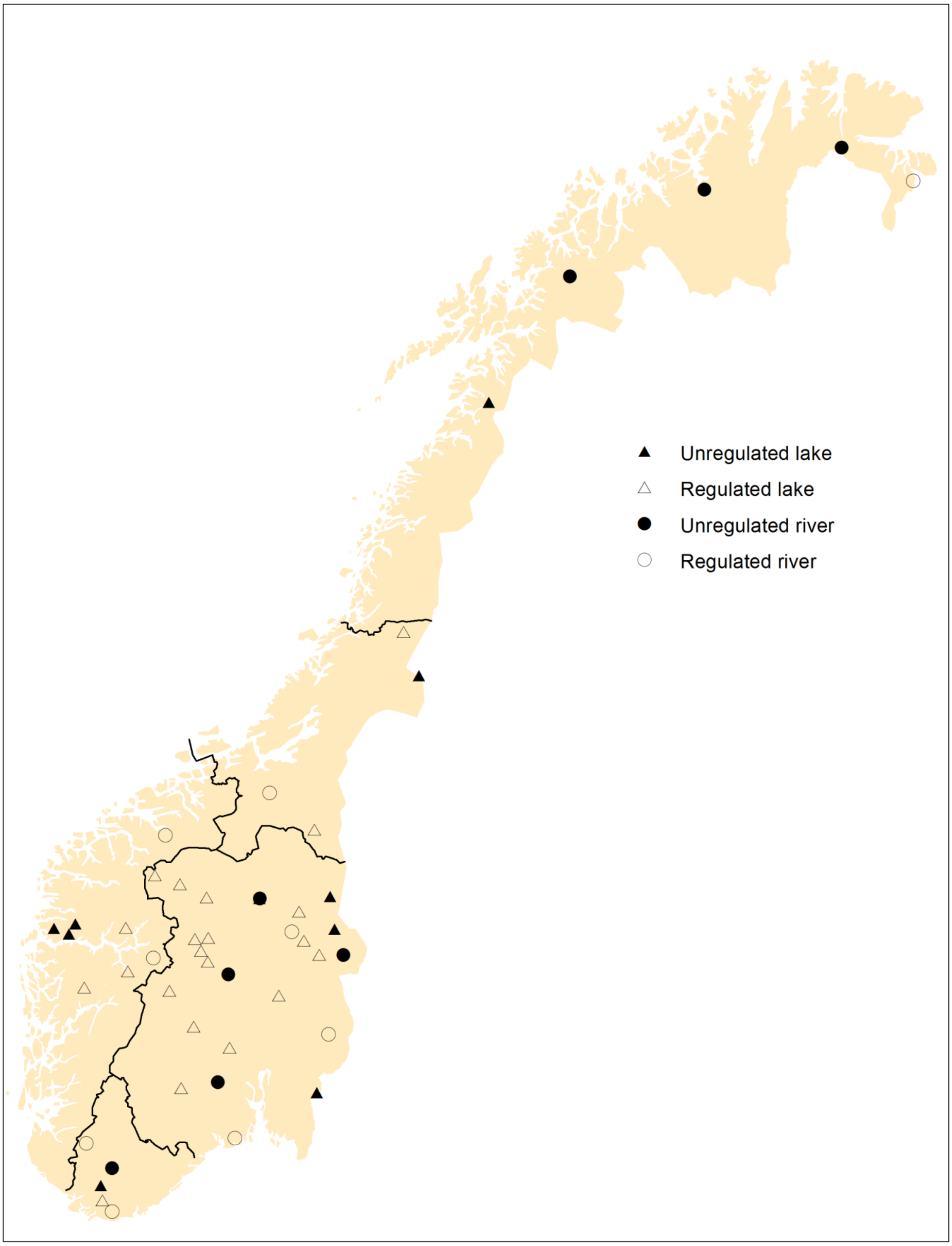


Figure 18: Spatial distribution of lake and river sites selected for the initial analysis.

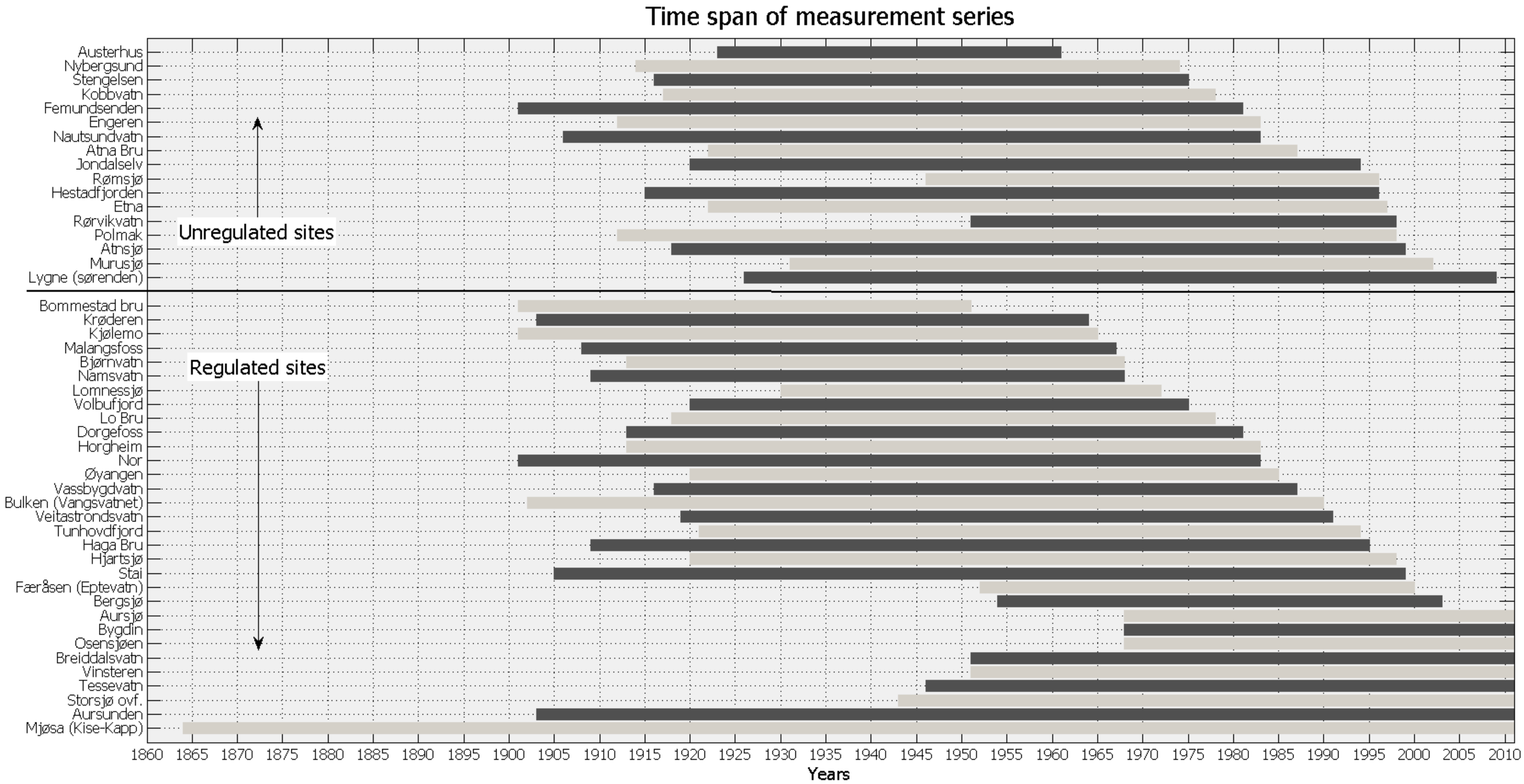


Figure 19: Data period for selected records.

Table 3: Summary of lake and river ice observation sites chosen for the initial quality control and homogeneity testing. A hyphen (—) indicate that the records were removed from the analysis prior to homogeneity testing due to a large percentage of missing values (> 15 %). An asterisk (*) denote stations where complete ice cover was not a yearly occurrence (see section 4.1.2).

		Station number	Station name	Location N	Location E	Elev. (MASL)	Freeze-up Period of record	Freeze-up Years of record	Break-up Period of record	Break-up Years of record	Ice cover duration Period of record	Ice cover duration Years of record
Lake stations	Regulated	2.375.1	Aursjø	61.9	8.3	1 098	1968 – 2011	44	1968 – 2011	44	1968 – 2011	44
		12.127	Bergsjø	60.7	8.3	1 082	1954 – 2003	49	1953 – 2002	50	1954 – 2001	48
		2.162	Bygdin	61.3	8.8	1 058	1968 – 2011	43	1968 – 2011	43	1968 – 2011	42
		2.167	Vinsteren	61.4	9.1	1 032	1951 – 2012	61	1951 – 2012	56	1951 – 2012	56
		2.15	Breiddalsvatn	62.0	7.6	900	1951 – 2012	62	1951 – 2012	60	1951 – 2012	60
		2.79	Tessevatn	61.8	8.9	854	1946 – 2012	60	1946 – 2012	60	1946 – 2012	59
		15.9	Tunhovdfjord	60.3	8.9	734	1921 – 1994	71	1920 – 1994	68	1921 – 1994	66
		2.111	Aursunden	62.7	11.5	690	1903 – 2011	107	1903 – 2011	106	1903 – 2011	105
		12.87	Øyangen	61.2	8.9	677	1920 – 1985	62	1920 – 1984	65	1920 – 1984	61
		139.5	Namsvatn	65.0	13.6	454	1909 – 1968	58	1909 – 1968	57	1909 – 1968	57
		2.82	Osensjøen	61.2	11.7	438	1968 – 2011	42	1968 – 2011	42	1968 – 2011	42
		12.89	Volbufjord	61.1	9.1	434	1920 – 1975	56	1920 – 1975	56	1920 – 1975	56
		2.132	Lomnessjø	61.7	11.2	256	1930 – 1972	43	1919 – 1997	66	1930 – 1972	40
		2.14	Storsjø[1]	61.4	11.4	251	1943 – 2011	*65	1934 – 2011	72	1943 – 2011	62
		23.2	Færåsen	58.2	7.3	232	1952 – 2000	49	1952 – 1998	46	1952 – 1998	46
		77.2	Veitastrondsvatn	61.4	7.1	170	1919 – 1991	*62	1922 – 1991	65	1922 – 1991	57
		16.32	Hjartsjø	59.6	8.8	157	1920 – 1998	70	1919 – 1998	74	1920 – 1998	67
		12.98	Krøderen	60.1	9.8	132	1903 – 1964	59	1900 – 1964	63	1903 – 1964	59
		2.825.39	Mjøsa (Kise-Kapp)	60.8	10.8	123	1865 – 2012	*140	1865 – 2013	142	1865 – 2013	140
		72.7	Vassbygdvatn	60.9	7.3	54	1916 – 1987	*68	1915 – 1987	69	1916 – 1987	66
		62.5	Bulken (Vangsvatnet)[2]	60.6	6.3	47	1902 – 1990	78	1925 – 1990	61	1925 – 1990	57
	Unregulated	2.131	Atnsjø[3]	61.9	10.2	701	1918 – 1999	77	1954 – 1998	44	1954 – 1998	44
		311.4	Femundsenden	61.9	11.9	662	1901 – 1981	80	1901 – 1980	78	1901 – 1980	77
		311.7	Engeren	61.5	12.1	472	1912 – 1983	70	1911 – 1983	70	1912 – 1983	67
		80.1	Rørvikvatn	61.2	5.8	336	1951 – 1998	48	1951 – 1997	47	1951 – 1997	47
		307.5	Murusjø	64.5	14.0	312	1931 – 2002	66	1935 – 2001	56	1950 – 2001	45
		24.13.13	Lygne (sørenden)	58.4	7.2	185	1926 – 2009	*74	1924 – 2009	75	1927 – 2009	69
		83.2	Hestadfjorden	61.3	5.9	146	1915 – 1996	*79	1915 – 1995	71	1915 – 1995	71
		314.3	Rømsjø	59.7	11.8	138	1946 – 1996	48	1945 – 1995	47	1950 – 1995	46
		82.1	Nautsundvatn	61.3	5.4	47	1909 – 1983	75	1926 – 1983	55	1926 – 1983	55

		167.3	Kobbvatn	67.6	16.0	8	1917 – 1978	60	1917 – 1978	61	1917 – 1978	60
River stations	Regulated	26.5	Dorgefoss	58.9	6.8	465	—	—	1913 – 1981	62	—	—
		73.1	Lo Bru	61.1	7.8	403	1918 – 1978	56	1917 – 1968	50	1918 – 1968	48
		2.117	Stai	61.5	11.1	256	1905 – 1999	93	1904 – 1998	94	1905 – 1998	92
		2.2	Nor	60.3	12.0	148	1901 – 1983	83	1911 – 1983	69	1911 – 1983	69
		122.2	Haga Bru	63.1	10.3	62	1909 – 1995	85	1913 – 1995	77	1913 – 1995	76
		103.4	Horgheim	62.5	7.8	55	1913 – 1983	57	1913 – 1983	62	1913 – 1983	53
		22.4	Kjølemo	58.1	7.5	40	1901 – 1965	*65	1900 – 1964	63	1901 – 1964	62
		246.1	Bjørnvatn	69.5	30.1	20	1913 – 1968	54	1913 – 1967	54	1913 – 1967	53
		15.18	Bommestad bru	59.1	10.1	5	1901 – 1956	52	1900 – 1958	57	1901 – 1956	52
	Unregulated	2.130	Atna Bru	61.9	10.2	701	1922 – 1987	63	1922 – 1987	61	1922 – 1987	61
		12.70	Etna	61.0	9.6	400	1922 – 1997	75	1922 – 2001	73	1922 – 1996	70
		311.6	Nybergsund	61.3	12.3	360	1914 – 1974	61	1909 – 1973	59	1915 – 1973	56
		22.5	Austerhus[4]	58.6	7.4	261	1923 – 1961	*38	1923 – 1961	37	1923 – 1961	36
		15.20	Jondalselv	59.7	9.6	180	1920 – 1994	70	1920 – 1994	75	1920 – 1994	70
		196.35	Malangsfoss	69.0	18.7	30	1908 – 1967	57	1908 – 1966	59	1908 – 1965	56
		212.2	Stengelsen	69.9	23.3	23	1916 – 1975	56	1916 – 1975	58	1916 – 1975	56
		234.1	Polmak	70.1	28.1	20	1912 – 1998	84	1912 – 1997	84	1912 – 1997	82

[1] Freeze-up data was sporadically available from 1911 with large data gaps until 1943.

[2] Break-up data was sporadically available from 1902 with large data gaps until 1925.

[3] Break-up data was available from 1918, but the years 1938 to 1953 were missing.

[4] The ice records for Austerhus (22.5) extend beyond 1959/61, but a water power scheme completed upstream in 1958/61 significantly increased the winter discharge (Tvede and Petterson, 1984). Most winters (80 %) post-regulation were ice-free.

3.3.3 Missing data

Missing data is a common challenge in observationally based studies, and can be due to numerous reasons. It could be missing due to instrument malfunction, because the observer got sick, was prevented from performing the observation as scheduled or simply forgot to enter the values into the observational log. The data could also have "disappeared" in the digitization process (Kundzewicz and Robson, 2000).

Missing data raise questions of data quality and can potentially make analysis more challenging, as not all statistical methods can cope with missing values. It is important to consider whether the data gaps are truly random or if data is missing with some kind of systematic bias. For example, if data are missing either in only cold or mild winters that would clearly bias the results. However, if the missing values are randomly distributed, it does not affect the results in any particular direction (Kundzewicz and Robson, 2000).

Data gaps in most ice records appeared to be random, with a few exceptions. Storsjø (2.14) and Vangsvatnet (62.5) appeared to be systematically missing ice observations in mild winters during the first 20 to 30 years of the records. The problem was attempted alleviated by omitting the problematic parts of the records (i.e. only using values after the gaps for trend analysis). No attempts were made to fill-in missing data.

3.3.4 Metadata

Information on which sites were affected by regulation was found using the NVE-Atlas (http://atlas.nve.no) and NVE reports on flood inundation mapping (Flomsonekartprosjektet). The website (http://glb.no/) of Glommens og Laagens Brukseierforening (GLB) did also serve as a useful source of information. A summary of the gathered metadata can be found in Appendix A.

Information on changes in observers, possible changes in the observer's location (relevant to lakes) or changes in guidelines for classification of ice cover were (unfortunately) not available, with the exception of Mjøsa.

Metadata of the Mjøsa record

Mjøsa is Norway's largest lake with a surface area of 369 km^2 (HRV) and a total volume in excess of 56 km^3. The lake is very deep with an average depth of 153 m and a maximum depth in the southern (middle) part of 453 m. Mjøsa is situated in Eastern Norway some 50 km north of Oslo. The ice observation record for Mjøsa is by far the longest ("continues") in Norway with both freeze- and break-up data available from 1865. However, the record is a composite series, based on data from several sources. A summary of the observational history is given in Table 4.

Table 4: Observational history of the composite Mjøsa series (NVE, 2013).

Period	Location of observations
1865 – 1895	The freeze and break-up dates were based on observations made by Captain Raabe aboard steam ships traversing the lake. Raw data and standardized values for certain areas of the lake data were presented by Holmsen (1901).
1896 – 1900	The freeze- and break-up dates were based on newspaper reports and observations made by the local population. Raw data and standardized values for certain areas of the lake data are found in Holmsen (1901).
1908 – 1923[1]	The freeze and break-up dates were based on observations made at Hamar vannmerke (2.101) located at Hamar brygge (eastern shore).
1924 – 1979	The freeze and break-up dates are based on private observations made by M. Karslund at Gjøvik (western shore).
1980 – 1989	The freeze and break-up dates are based on observations made by M. Karslund on behalf of the NVE at Gjøvik. It was supplemented with ice maps made by O. Årnes on the stretch from Kise to Minnesund.
1990 – today	The freeze and break-up dates are based on ice maps made by O. Årnes. From the winter of 1995/96 ice observations from Kise research farm are also used. The farm is located on the eastern shore a couple of kilometers south of Gjøvik.

[1]Ice observations continued at Hamar vannmerke (2.101) until 2001, but the station was relocated to Hamar water works approximately 3 km towards the northwest in 1966. There is a 42-year period where observations from Hamar and Gjøvik overlap.

As mentioned (Table 4), Holmsen (1901) provided standardized freeze- and break-up dates for certain areas or transects of Mjøsa, though slightly different transects were available for the two. The NVE has chosen to construct a Mjøsa-record composed of freeze-up and break-up dates for "Hamar – Nes – Toten" and "Hamar – Nes – Gjøvik", respectively. Today's observations are for a location (Kise – Kapp) somewhere in between these two (Personal communication, Ånund S. Kvambekk/NVE).

The quality and accuracy of the data during the 1865 – 1900 period is probably high, considering that it was based on notes made by people who were very dependent on the ice conditions of the lake. A seven year data gap occurs between 1901 and 1907, before ice observations are continued at Hamar vannmerke (2.101). From 1924 the Mjøsa record is based on ice observations from Gjøvik at the opposite shore of the lake. Ice observations continued at the same location at Hamar to 1965, giving a 42-year period where observations from Hamar and Gjøvik overlap, making a side-by-side comparison possible.

4 Methodology

High-quality (homogenous) data is essential for all meteorological and hydrological analyses. Erroneous data and homogeneity breaks can cause apparent changes in long-term meteorological and hydrological time series, which may distort the true (climate) signal (Tuomenvirta, 2002). Ideally a time series used for analysis should be long, homogenous and with few missing values. In the real world these standards are often not met, and one must simply work with the available data.

4.1 Practical challenges working with ice records

Unlike trend studies of temperature and discharge, single-site and regional trend analysis of ice records is not necessarily a straight forward process. Freeze-up and break-up dates must be defined clearly, and the definition must be enforced consistently at all sites. The definitions must also be consistent through both time and space for the results to be comparable.

In addition, some lakes and rivers do not freeze completely every winter. This is typical for deep low-lying lakes and rivers with a strong maritime influence in Southern and Eastern Norway. These years must also be included in the trend analyses, and a consistent approach for handling of such cases is important.

4.1.1 Freeze-up dates, break-up dates and ice cover duration

Studies on trends in ice conditions have used different definitions of freeze- and break-up dates. Assel and Robertson (1995) defined freeze-up as the date when solid ice cover (analogous to "complete ice cover") had formed out to a given point in the lake they studied. Break-up was defined as the date when the ice cover disappeared or moved out-of-sight (analogous to "ice free") at the same point. In winters with multiple occurrences of freeze- and break-up, the first freeze-up and the last break-up were used. A similar approach to Assel and Robertson's (1995) was used in the thesis. Freeze- and break-up dates were determined in the following manner:

- Freeze-up date (FUD): The first time during autumn or winter the lake or river is classified as "completely ice covered".
- Break-up date (BUD): The last time during winter or spring the lake or river is classified as "ice free".

- Ice cover duration (ICD): The difference (in days) between the freeze-up and break-up dates.

The reason for choosing "complete ice cover" instead of "partial ice cover" (or both) was due to homogeneity considerations. "Partial ice cover" is undoubtedly more subjective than "complete ice cover", i.e. what constitutes "partial ice cover" is likely to vary more between the observers than the former – even though the same guidelines are used. Most of the records used in the thesis have almost certainly changed observer several times, and the guidelines for assessment of ice cover have possibly changed too. It is likely that absolutes (i.e. ice/no ice) are less influenced by the above.

A modified version (Robertson et al., 1992; Assel and Robertson, 1995) of Julian dates, including the extra day in leap years, was used for all analyses in the thesis. Freeze-up day numbers were computed as days from 1st January of the year preceding break-up, while break-up day numbers were computed as days from 1st January of the year of break-up. Thus, 1st January of the year in which break-up occurs is day 366 for freeze-up dates (or 367 – depending on whether the previous year was a leap year).

4.1.2 Years without complete ice cover

Of the 48 sites selected for initial analyses 40 were completely ice covered for some duration every winter. The remaining eight stations (Table 5) did not have complete ice cover in *at least* one winter. Extremes ranged from Mjøsa, which lacked complete ice cover in nearly 25 % of the winters, to Veitastrondsvatn where complete ice cover did not form only once in a 73 year observation period from 1919 to 1991.

Table 5: Sites where ice cover was not a yearly occurrence. (L) and (R) denotes whether it is a lake or river site.

Station number	Station name	Years without complete ice cover: Years	Years without complete ice cover: of total
2.825.39 (L)	Mjøsa (Kise – Kapp)	34	24 %
22.5 (R)	Austerhus	4	11 %
2.14 (L)	Storsjø	6	9 %
22.4 (R)	Kjølemo	5	8 %
24.13.13 (L)	Lygne (sørenden)	3	4 %
72.7 (L)	Vassbygdvatn	2	3 %
83.2 (L)	Hestadfjorden	2	3 %
77.2 (L)	Veitastrondsvatn	1	2 %

For ice cover duration the quantification of these no-ice years are straightforward, i.e. the duration is zero days. The challenge lies in how to deal with the freeze- and break-up dates in such winters. One approach is to simply ignore ice-free winters in the analysis and treat them as missing values. However, that would clearly bias the results towards earlier freeze-up and later break-up. Robertson and Assel (1995) and later Jensen et al. (2007) suggested that freeze- and break-up dates for such situations should be inferred by taking the average midpoint for freeze- and break-up dates of the five winters with the shortest ice durations. Their approach has been followed in this thesis, but similar to Jensen et al. (2007) two alternative methods have also been used for comparison purposes. The alternative methods were: (a) winters without ice cover were left out; and (b) latest observed freeze-up date and earliest observed breakup date were used.

4.2 Quality control of ice records

The first step in the analysis of any time series should be to plot the data. Graphs provide crucial information that is difficult to obtain in any other way. To simply compute statistical measures without looking at a plot can be an invitation to misunderstanding the data. Graphs provide visual summaries of data which more quickly and completely describe essential information than do tables of numbers (Hensel and Hirsch, 2002). Chambers et al. (1983) for instance explained the reason for and benefit of visual inspection of graphs in data analysis as follows:

"There is no single statistical tool that is as powerful as a well-chosen graph. Our eye-brain system is the most sophisticated information processor ever developed, and through graphical displays we can put this system to good use to obtain deep insight into the structure of data."

The process of data control and error detection is illustrated in Figure 20. All stations and parameters were inspected visually using time series plots (Figure 21) in combination with box plots (Figure 22).

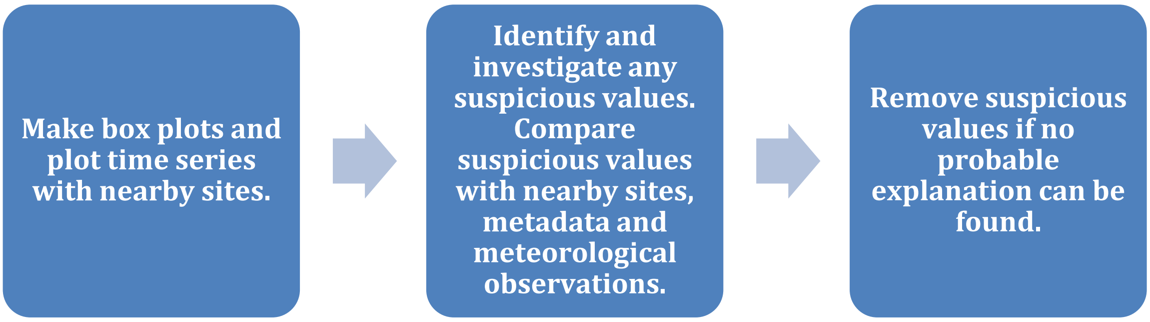


Figure 20: Flow chart illustrating the process of data control and error detection.

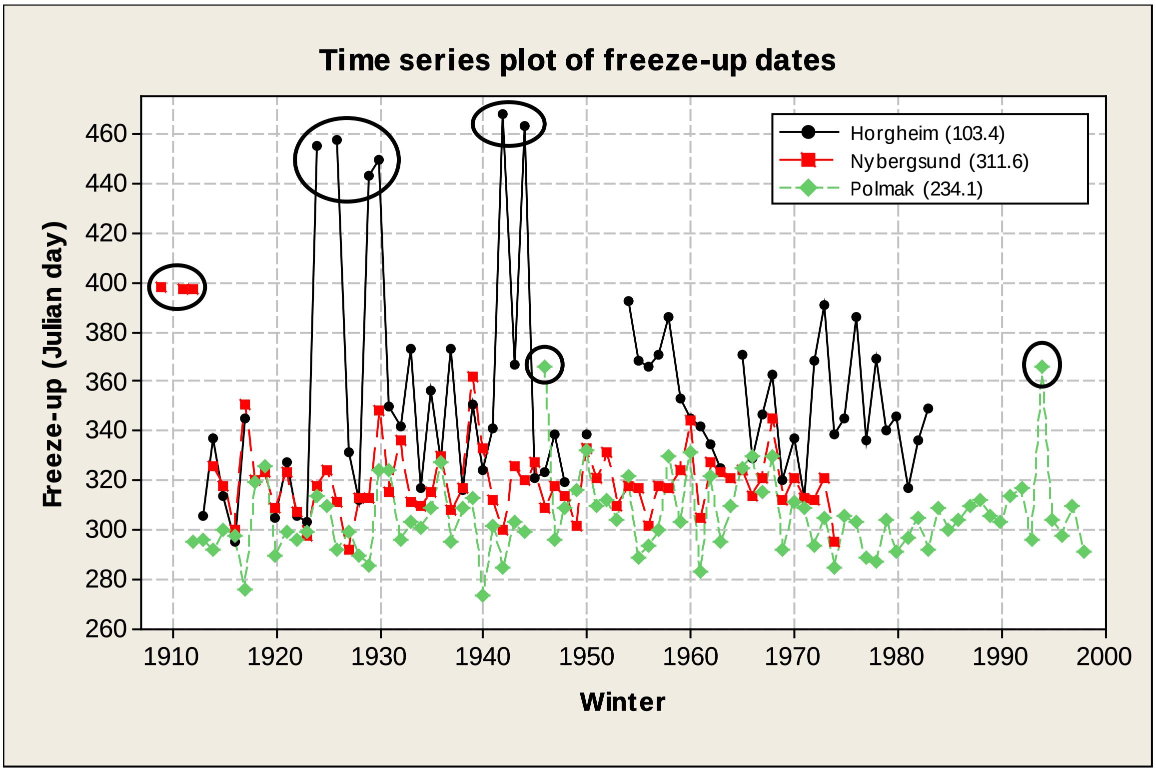


Figure 21: Time series plot of freeze-up dates for Horgheim (103.4), Nybergsund (311.6) and Polmak (234.1). Outliers are marked with a circle. The subsequent inspection of the outliers revealed that all of them were incorrect, and likely due to a punching error. The two outliers in the Nybergsund record not circled in Figure 22 were found to be probable when comparing with nearby stations and hydro-meteorological data. It must be stressed that Horgheim, Nybergsund and Polmak are <u>not</u> nearby sites. The figure is for illustrative purposes only.

A commonly used method to summarize the distribution of a data set (and to detect outliers in a data set) is a box plot (Figure 22). It is a graphical summary of a sample that shows its shape, central tendency (median) and the dispersion of the data. A standard box plot represents the first quartile (Q_1), the third quartile (Q_3), the median (Q_2) and the inter-quartile range (IQR) which is defined as $Q_3 - Q_1$. It will also show whiskers which extend out to $[Q_1 - 1{,}5IQR]$ and

$[Q_3 + 1{,}5IQR]$. Observations that fall outside the whiskers are classified as outliers (Hensel and Hirsch, 2002).

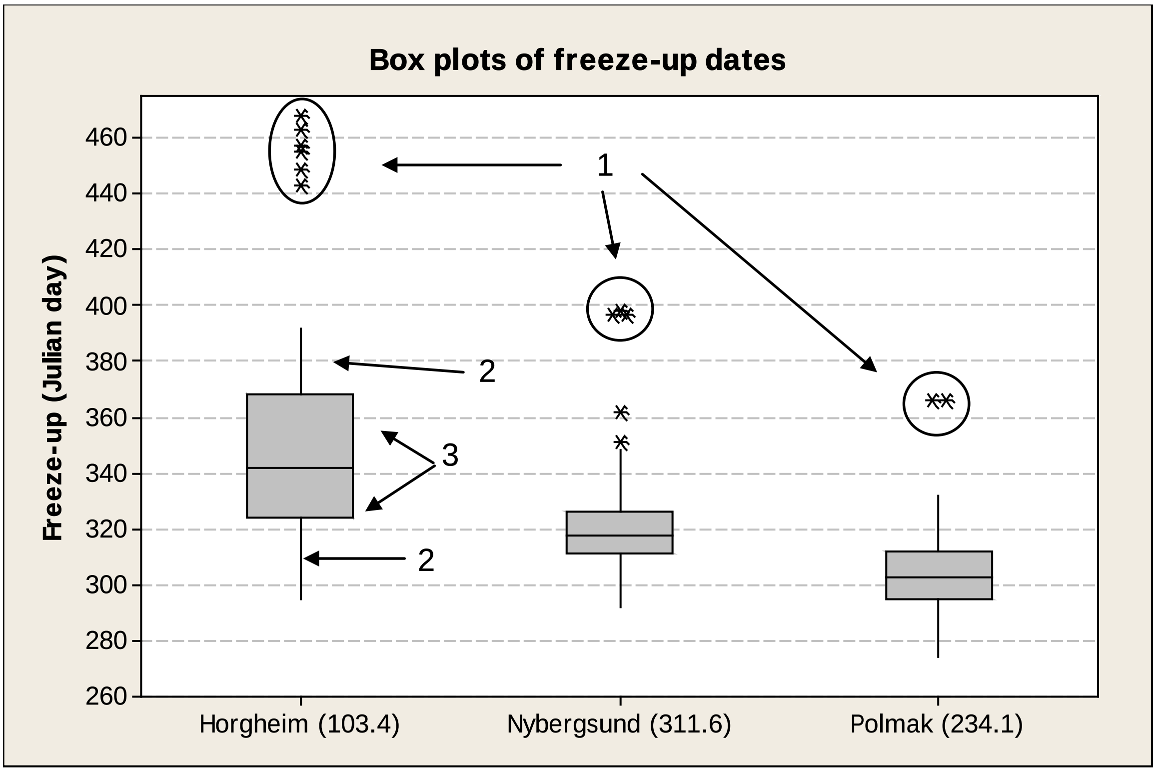


Figure 22: Box plot of freeze-up dates for Horgheim (103.4), Nybergsund (311.6) and Polmak (234.1). The numbers indicate; 1) Outlier (*), i.e. observations that are beyond the upper and lower whisker, 2) Upper and lower whisker, 3) Inter-quartile range (IQR). In the case of Horgheim the outliers are 443, 449, 455, 457, 463 and 468. The whiskers extend from 295 to 392.

In statistics, an outlier is generally defined as an observation that appears to deviate markedly from other observations in a data set. There is a low probability that it originates from the same statistical distribution as the other observations (Grubbs, 1969). It is usually indicative of some kind of error (observation, measurement, punching etc.) or that the population has a heavy-tailed distribution. If the outliers are indeed errors one could discard them or use statistics that are robust to outliers. If the outliers are indicative of a distribution with high kurtosis one should be very cautious of using statistical methods that assume a normal distribution (Gilbert, 1987).

In any case, when an outlier is encountered in a data set, further analysis should be carried out to find the cause of the outlier. As a general rule, the hydrologist should be conservative in carrying out any corrections to the data. If any alterations are made to the data it should always be done using assumptions based on evidence rather than any element of guesswork. However, some degree of subjectivity in the process is unavoidable. Any alterations should also be recorded in such a way that others can easily follow what has been done – and why (WMO, 2008).

4.2.1 Normality of ice phenology data

Normality of the data is an underlying assumption of several commonly used (parametric) methods in homogeneity testing and trend analysis. Hence, it is important to check if the assumption is also valid for ice cover data. Normal probability plots were made for all sites and parameters (freeze-up, break-up and ice cover duration) and inspected visually. In addition, all records were tested for departure from normality using the powerful Anderson-Darling (A-D) test. The A-D test is a modification of the Kolmogorov-Smirnov (K-S) test, where the former gives more weight to the tails of the distribution than the latter. Moreover, the A-D test makes use of the specific distribution (here: the normal distribution) in calculating critical values, wheras the critical values of the K-S test does not depend on the specific distribution being tested (i.e. "distibution free") (Razali and Wah, 2011). The null and alternative hypotheses for the A-D test are:

H_0: The data follows a specified distribution (here: the normal distribution).
H_1: The data do not follow a specified distribution.

If the p-value of the computed Anderson-Darling test statistic is lower than the chosen significance level, one can conclude that the data do not follow the specified distribution. Complete results of the individual tests are given in Appendix B. A majority of the records (Table 6) was found to be normally distributed, but a considerable portion was not. As a general pattern, the ice cover duration appeared to be somewhat more normally distributed than freeze- and break-up dates. Examples of some extremities are shown in Figure 23 and Figure 24. As the purpose of the normality testsing was to improve the basis for decisions in regards to the homogeneity testing, no specific significance level were assumed.

Table 6: Outcome of the Anderson-Darling test for normality on all records. The first figure indicates the number of stations where the test failed to reject the null hypothesis at the given significance level (α), i.e. the data follows the normal distribution.

Significance level (α)	Freeze-up	Break-up	Ice cover duration
0.01	33 (72 %)	32 (68 %)	39 (83 %)
0.05	25 (50 %)	30 (64 %)	30 (64 %)

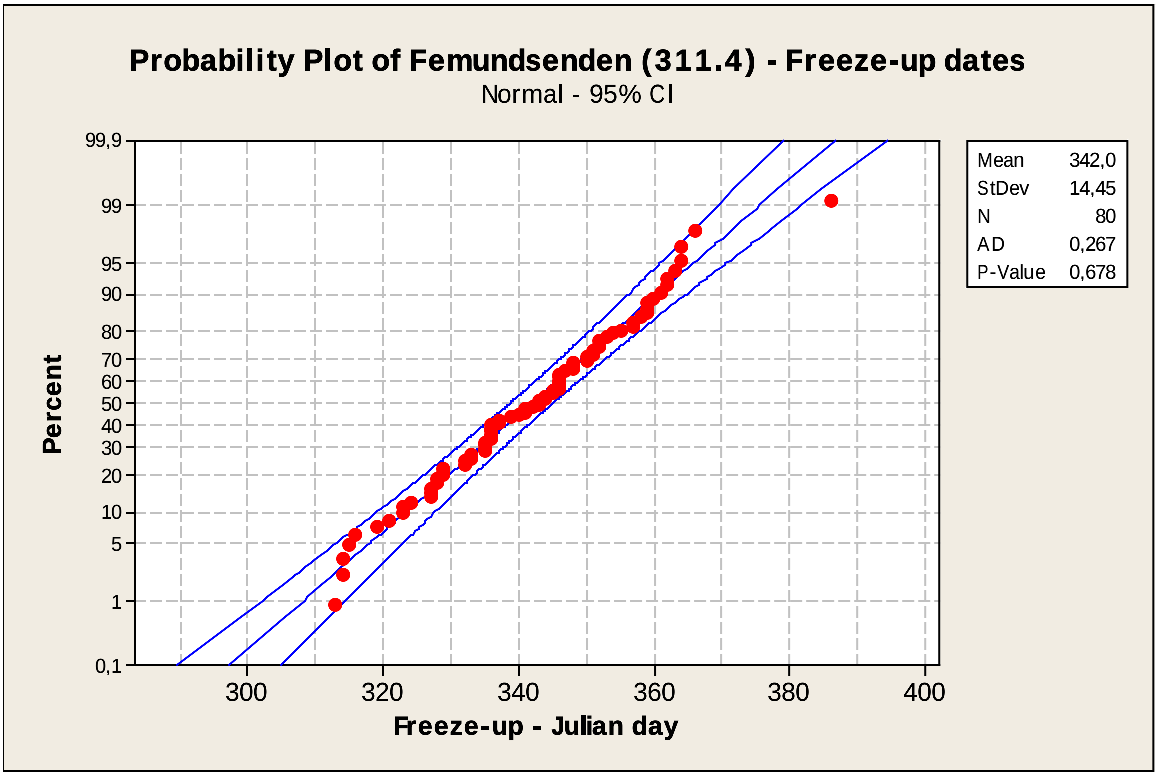


Figure 23: Normal probability plot of break-up dates for Femundsenden (311.4). Both the plot and the AD-statistic indicate that the data are normally distributed.

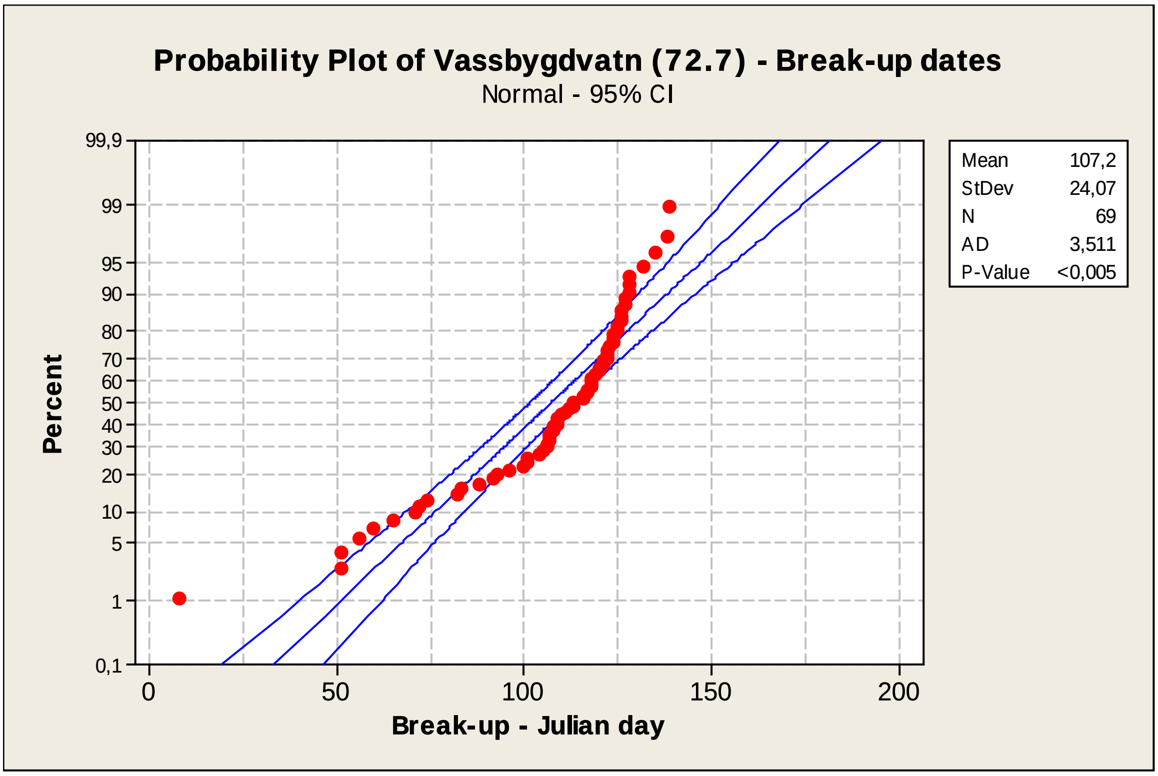


Figure 24: Normal probability plot of break-up dates for Vassbygdvatn (72.7). Both the plot and the AD-statistic clearly show that the values/observations are non-normal. The bow shaped probability plot indicates that the data have excessive skewness (i.e. it is not symmetrically distributed). A convex pattern is apparent when the data are skewed to the left.

4.3 Homogeneity testing of ice records

A time series can be considered to be homogenous if a change in the data reflects a change in meteorological or hydrological conditions, rather than a change in the conditions under which the observations were made (Trevin, 2007). To accomplish this, the observations should have been consistently performed using the same method, with the same undamaged instrumentation, at the same time and place, and in the same environment. However, this is rarely the case for long time series. At most old stations the original instruments have been replaced, often several times, the surrounding vegetation and buildings have changed, and in some cases the station itself has also been relocated (Peterson et al, 1998; Tuomenvirta, 2002). In the case of ice observations two types of inhomogeneities are thought to be relevant:

- Ice observations are subjective and observer dependent. Changes in the observer, the location of observations or the guidelines for classification of ice cover can lead to changes in the observed dates for freeze- and break-up, even though there have not been any actual changes.

- Regulation of the water course for hydropower production can lead to actual changes in freeze- and break-up.

As such, ice observations could have been performed at the same location, by the same observer following the same guidelines throughout entire period, and the effects of regulations could still have introduced inhomogeneities in the records, that is, if the purpose was to analyze long-term natural trends unaffected by human activities.

4.3.1 Approaches to testing for homogeneity

Extensive work has been done on inhomogeneities in hydrological and meteorological time series. Reviews of the most commonly used techniques can be found in Peterson et al. (1998) and Kundzewicz and Robson (2000; 2004). Unfortunately, there are limited studies on the prescience and detection of homogeneity in ice records. However, methods used for other hydro-meteorological variables are likely also applicable for ice records.

Studies show that a combination of metadata and statistical methods is the most effective way to identify inhomogeneities (Wijngaard et al., 2003). The advantage of metadata is that it can provide information on when possible non-climatic heterogeneities were introduced into a time series, as well as the exact cause of the heterogeneities. Unfortunately, in the case of ice observations, metadata were for the most part lacking. As such, the homogeneity assessment was mainly based on statistical analyses.

It is generally recommended that homogeneity testing of hydro-meteorological data is performed relatively (comparison between stations) as opposed to absolute. Testing only the data from individual stations can be problematic, mainly because the change (or lack thereof) one detects may be caused by (or masked) by real changes in the climate (Peterson et al., 1998). However, when two series are not sufficiently correlated, absolute tests, which only use the single-station series, are considered more powerful (Wijngaard et al., 2003). Analyses of the ice records showed that freeze- and break-up dates, as well as the duration of ice cover, were generally poorly correlated between the sites. R^2-values of nearby sites were typically ~0.25 or lower. Hence, an approach based on relative homogeneity between sites was not considered suitable for this study.

A similar problem was encountered by Wijngaard et al. (2003) who explored possible methods for detecting homogeneity breaks in daily temperature records from the European continent. Relative testing was found to be a nonviable option in this study due to the relatively sparse spatial distribution of the station network. The homogeneity assessment was therefore restricted to absolute tests. A two-step approach was employed: Four different tests for absolute homogeneity were applied, and the records were then grouped into reliability classes based on the results. Similar techniques have also been utilized by Sahin and Cigizoglu (2010) and Martínez et al. (2010). The approach suggested by Wijngaard et al. (2003) has been used in this thesis, with some revisions. The tests used by Wijngaard et al. (2003) and in this thesis were the

- Standard normal homogeneity test (SNHT) for single break (Alexandersson, 1986)
- Buishand range test (Buishand, 1982)
- Pettitt test (Pettitt, 1979)
- Von Neumann ratio test (Von Neumann, 1941)

All four tests assume a null hypothesis (H_0) where the annual values (Y_i) of the testing variable (Y) are independent and identically distributed (IID). Under the alternative hypothesis (H_1) the first three tests assume that a step-wise shift in the mean is present. The alternative hypothesis (H_1) of the Von Neumann ratio test is that the data is not randomly distributed. The first three tests are capable of locating the year when a break likely occurred (location specific), wheras the Von Neumann ratio test is not (Wijngaard et al., 2003).

Although the location specific tests share several characteristics, they also differ in some regards. The Buishand and Pettitt tests are generally thought to be more sensitive to breaks near the middle of a time series, while the SNHT is more sensitive to breaks in the beginning and the end of time series (Wijngaard et al., 2003) – although there has been some discussion lately on the latter (Toreti et al., 2011).

The Pettitt test is non-parametric and based on the ranks of the elements (instead of the actual values themselves), while the other tests are parametric and assume that the Y_i-values are normally distributed. This clearly complicates the testing procedure, as several of the ice records are not normally distributed (Table 6). However, the departure from normality is not necessarily large for most ice records, hence the results of the parametric tests could still be useful. In any case, care should be taken in the interpretation of the test results. If the record in question is clearly non-normal and all parametric tests detect a break, while the Pettitt test does not, the latter should be given precedence.

Wijngaard et al. (2003) classified the time series as either "useful", "doubtful" or "suspect" based on the number of tests that rejected the null hypothesis at the 1 % significance level (α). The criterions for classification as well as the qualitative interpretation of the classes are given in Table 7.

Table 7: Criterions for classification of records based on the results of the absolute homogeneity tests. "Rejections of H_0" is the number of tests that rejected the null hypothesis at the 1 % level. Qualitative interpretation of the classes is based on Wijngaard et al. (2003).

Class	Rejections of H_0	Description
Class 1: "Useful"	0 – 1	No clear signal of an inhomogeneity is apparent in the record. The record appears to be sufficiently homogenous for trend analysis.
Class 2: "Doubtful"	2	There are indications of an inhomogeneity in the record. The magnitude of the inhomogeneity likely exceeds the level expressed by the inter-annual standard deviation of the tested variable. Results of trend analyses should be regarded critically due to the possible existence of inhomogeneities.
Class 3: "Suspect"	3 – 4	It is likely that an inhomogeneity is present in the record. The magnitude of the inhomogeneity exceeds the level expressed by the inter-annual standard deviation of the tested variable. Results of trend analyses should be regarded very critically due to the probable existence of inhomogeneities. Large trends may be related to an actual climate signal, but marginal trends should be considered spurious.

As a general rule, records labeled "suspect" should not be used for trend analysis. In some special cases the identified breaks could be due to actual climate signals rather than an artificial break. Martínez et al. (2010) showed that some natural events (two large volcanic eruptions – El Chichón in 1982 and Mt. Pinatubo in 1991) were identified as homogeneity breaks by the testing procedure. However, this is considered less likely for the time series examined in this thesis.

4.3.2 Adjustments to the Mjøsa record

As described in section 3.3.4, the Mjøsa record is a composite series constructed of observations made from several locations around the lake. Concurrent ice observations were available from Hamar vannmerke and Gjøvik (Karslund) over the period of 1924 to 1963. Hence, a side-by-side comparison of freeze- and break-up dates could be performed. The results (Table 8) showed that ice cover was established somewhat later at Gjøvik than at Hamar (three days). The same was true for break-up, which occurred almost four days later at Gjøvik. Total duration of ice cover was more or less the same at both sites (<0.5 days difference).

Table 8: Comparison of freeze-up dates, break-up dates and ice cover duration Hamar vannmerke (2.101) and Gjøvik (Karslund) over the 1924 – 63 period.

	Freeze-up (Julian day)	Break-up (Julian day)	Ice cover duration (days)
Gjøvik	398	118	85
Hamar	395	114	84
Difference	3	4	<0.5

Given the differences in ice cover between Hamar vannmerke and Gjøvik, both freeze- and break-up dates were adjusted in the 1908 – 23 period to avoid homogeneity breaks in the record. The observations during the 1908 – 23 period were adjusted by adding the computed difference over the 1924 – 63 period to the record. Differences in ice cover duration were considered negligible and were thus not adjusted. The described homogeneity tests were run on the adjusted record. Meteorological observations (eKlima, 2013) show that the missing years (1901 – 1907) were a mix of cold and warm winters, hence it should nokt introduce a systematic bias in the trend analysis these years are ignored (i.e. treat them as missing values, which they are).

4.4 Trend analysis

Statistical trend analysis is in essence a hypothesis-testing process. The null hypothesis (H_0) of trend tests is usually that there is no trend in a time series, i.e. the observations are randomly distributed (ordered) in time. However, the underlying assumptions (type of distribution, serial correlation etc.) and the precise mathematical definition of what constitutes is meant by "no trend" varies from test to test (Hensel and Hirsch, 2002).

The outcome of the test is a "decision", i.e. H_0 is either rejected or not. It should be noted that a failure to reject the null hypothesis (H_0) does not prove that there is no trend. Rather, it is a statement that the available evidence is not sufficient to conclude, with a specified level of confidence (α), that there is a trend (Hensel and Hirsch, 2002). Possible outcomes of a statistical test are given in Table 9.

Table 9: Probabilities associated with possible outcomes of a trend test. Based on Hensel and Hirsch (2002).

	True situation	
Decision	No trend. H_0 true.	Trend exists. H_0 false.
Failure to reject H_0. "No trend"	Probability = $1 - \alpha$	(Type II error) β
Reject H_0. "Trend"	(Type I error) Significance level α	(Power) $1 - \beta$

α = P (reject $H_0|H_0$ true) and β = P (reject $H_0|H_0$ false)

The power ($1 - \beta$) of a statistical test is the probability of correctly rejecting the null hypothesis when it is false. This can only be assessed if the sampling distribution of the test statistic under the alternative hypothesis is known. However, that is rarely the case, and a test must therefore be found which has high power for the kind of data expected to be encountered (Hensel and Hirsch, 2002).

4.4.1 Approaches to testing for trend

Previous studies on trends in ice phenology have used a variety of methods, both parametric and non-parametric. Recent studies have mainly used either linear regression (Magnuson et al., 2000; Korhonen, 2006; Jensen et al., 2007; Kvambekk and Melvold, 2010) or the Mann-Kendall trend test in combination with the Theil–Sen estimator (Hodgkins et al., 2002; Duguay et al., 2006, Dibike et al., 2011; Gebre and Alfredsen, 2011).

Linear regression

Simple linear regression is one of the most commonly used methods in trend analysis. A linear regression model is fitted to the data with the following structure

$$Y_i = \beta_0 + \beta_1 x_i + \varepsilon_i, i = 1, \dots, n \qquad (4)$$

where Y_i is the response variable, x_i is the predictor variable and ε_i is some unknown error component assumed to be independent and normally distributed (Bhattacharyya and Johnson, 1977). The significance of the trend is found performing a significance test on β_1 (slope of the regressions line). The null hypothesis (H_0) of the test is that slope coefficient of the regression line is zero ($\beta_1 = 0$). This is usually tested against the two-tailed alternative ($\beta_1 \neq 0$). As with all statistical analyses, the assumptions made in the model formulation must also be compatible with the data. Linear regression is based on four assumptions:

(a) There is a linear relationship between the dependent and independent variables.
(b) The errors are independent (no serial correlation).
(c) Homoscedasticity (constant variance) of the errors versus time
(d) The data follows a normal distribution (i.e. the errors are normally distributed)

Any violations of linearity should be considered serious. For example, if the relationship between x and y forms a curve rather than a straight line, any predictions obtained from a straight-line model fitted to the data is likely to yield nonsensical results. Violations of independence are also serious, as it will distort the conclusions drawn from t-tests and the confidence statements associated with interval estimation. Heteroscedasticity (c) make it difficult to gauge the true standard deviation of the forecast errors, usually resulting in confidence intervals that are either too wide or too narrow. Departure from normality (d) will compromise the estimation of coefficients and the calculation of confidence intervals which are all based on the assumptions of normally distributed errors (Bhattacharyya and Johnson, 1977).

Studies have shown that while parametric tests generally have higher power when *all* assumptions are met, this advantage will rapidly diminish with even small violations of the assumptions. Hirsch et al. (1991) and Yue and Pilon (2004) demonstrated that the non-parametric Mann-Kendall test clearly outperformed (more powerful) linear regression with even small departures from normality. In light of this, a non-parametric approach was chosen for the trend analyses. Even though majority of the ice records (Table 6) do follow the normal distribution, a fairly large percentage does not. The credibility (and comparability) of the analysis is enhanced if the same statistical method is used for all the data sets in the study (Hirsch et al., 1991).

The Mann-Kendall test

The Mann-Kendall test (M-K) is a non-parametric statistical test that has been widely used for identifying trends in meteorological and hydrological time series. It has also been used in several studies of trends in ice phenology (Hodgkins et al., 2002; Duguay et al., 2006, Dibike et al., 2011; Gebre and Alfredsen, 2011). The M-K test has several advantages over linear regression. It can be applied to all types of data as no assumption of normality is required. Furthermore, it can cope with missing values and has a fairly low sensitivity to abrupt changes in the time series (Hensel and Hirsch, 2002). As with linear regression, there must be minimal serial correlation in the time series for the resulting Z-statistics and p-values to be correct. This is unfortunately not the case with many hydrological processes, which often exhibits at least some degree of autocorrelation (Yue and Wang, 2002). However, correlograms (autocorrelation plots) of ice observations showed that there were minimal autocorrelation in the records.

The M-K test can be used in situations when the data values x_i of a time series can be expected to follow the model

$$x_i = f(t_i) + \varepsilon_i \tag{5}$$

where $f(t)$ is a continuous monotonic (increasing or decreasing) function of time and the residuals ε_i can be assumed to belong to the same distribution with a zero mean (Salimi et al., 2002). It is also assumed that the variance of the distribution remain constant over time (homoscedasticity), though not necessarily in the original units[3] (Hensel and Hirsch, 2002).

The null hypothesis (H_0) of the M-K test is that there is no trend, i.e. the observations $(x_1, \dots; x_n)$ are a sample of n independent and identically distributed random variables. The alternative hypothesis (H_1) is that there is an increasing or decreasing monotonic trend. The test statistic S (Salimi et al., 2002) is computed using the following formula

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(x_j - x_k) \tag{6}$$

where x_j and x_k are the sequential data values in years j and k, with $j > k$ and

[3] If a monotonic transformation (such as the ladder of powers) is used to achieve constant variance in the time series, the test statistic will be identical to that for the original units. This is due to the fact that the M-K test is invariant to (monotonic) to power transformations (Hensel and Hirsch, 2002).

$$sgn(x_j - x_k) = \begin{cases} 1 & if \quad x_j - x_k > 0 \\ 0 & if \quad x_j - x_k = 0 \\ -1 & if \quad x_j - x_k < 0 \end{cases} \tag{7}$$

Mann (1945) and Kendall (1975) have shown that when $n \geq 10$, the test statistic is approximately normally distributed with mean

$$E(S) = 0 \tag{8}$$

and variance

$$Var(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(t_p - 1)(2t_p + 5)\right] \tag{9}$$

where q is the number of tied groups and t_p is the number of data points in p^{th} tied group. The standardized test statistic Z is computed as follows

$$\mathrm{Z} = \begin{cases} \dfrac{\mathrm{S}-1}{\sqrt{\mathrm{Var(S)}}} & \text{if} \quad \mathrm{S} > 0 \\ 0 & \text{if} \quad \mathrm{S} = 0 \\ \dfrac{\mathrm{S}+1}{\sqrt{\mathrm{Var(S)}}} & \text{if} \quad \mathrm{S} < 0 \end{cases} \tag{10}$$

The existence of a statistically significant trend is assessed using the Z-value. In a two-tailed test for trend, the H_0 is rejected if $|Z| \geq Z_{1-\alpha/2}$ where $Z_{1-\alpha/2}$ can be obtained from the standard normal cumulative distribution tables. A positive value of Z indicates an upward trend (increasing values with time) while a negative value of Z indicates a downward trend (Salimi et al., 2002). Corresponding p-values $(p = 2[1 - \Phi(|Z|)])$ were also computed for illustrative purposes. The p-value is the probability of obtaining a test statistic at least as extreme as the one that is observed given that the null hypothesis is true. The smaller the p-value, the more contradictory is the data to H_0 (Devore and Berk, 2007).

Various significance levels (α) have been used in studies on trends ice phenology, ranging from 10 % (Duguay 2006; Gebre and Alfredsen 2011) to 5 % (Magnuson et al. 2002; Bosnal et al. 2006; Korhonen, 2006; Kvambekk and Melvold, 2010) or lower (Jensen et al. 2007). For the trend analyses in this thesis a significance level of 5 % were chosen.

4.4.2 Theil-Sen slope estimator

Trend magnitudes were estimated using the non-parametric median based Theil-Sen slope estimator (also known as Sen's slope). It was first proposed by Theil (1950) and later developed by Sen (1968) to handle cases were two samples have the same x-coordinate. The Theil-Sen estimator is robust, i.e. it is resistant to the presence of gross data errors or outliers, which can cause problems with least-squares regression, and it can be computed when data are missing. Comparisons show that it is actually competitive with least-squares regression even when the data are normally distributed and outliers are absent (Hensel and Hirsch, 2002; Foster, 2013).

The slope (m) is estimated as the median of all pairwise slopes between each pair of values in the data set (Theil, 1950; Sen, 1968; Hensel and Hirsch, 2002). Each individual slope estimate (m_{ij}) is calculated using the equation

$$m_{ij} = \frac{(y_j - y_i)}{(t_j - t_i)} \; for\; i < j \; and\; i = 1, 2, \dots, n-1;\; j = 2, 3, \dots, n \qquad (11)$$

The number of possible slopes between data pairs is given by

$$N_p = \frac{n(n-1)}{2} \qquad (12)$$

The computed slope estimates are sorted and ranked from lowest to highest. If N_p is an odd number, the median slope is the middle value of the array. If N_p is an even number, the median is calculated as the arithmetic average of the two middle values (Hensel and Hirsch, 2002).

4.5 Spearman's rank correlation coefficient

Links between ice phenology and hydro-meteorological variables (air temperature and discharge) were examined using the Spearman's rank correlation coefficient, as the relation did not appear to be linear at most sites.

Spearman's rank correlation coefficient is the non-parametric analogue of Pearson's correlation coefficient. It evaluates how well an arbitrary monotonic (generally increasing or decreasing) function describes the relationship between two variables, without making any other assumptions about the particular nature relationship between the variables (Bhattacharyya and Johnson, 1977; Hensel and Hirsch, 2002). It is calculated by

$$\rho = \frac{\sum_i (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_i (x_i - \bar{x})^2 \sum_i (y_i - \bar{y})^2}} \tag{13}$$

where ρ is the Spearman rank correlation coefficient and x_i/y_i are the ranks of the data pairs which are to be tested. If the correlation is positive (negative), higher ranks of x will be paired with higher (lower) ranks of y, and their product will be large (small). In the case of no correlation, the association between the x and y ranks will only be a random pattern. Hence, ρ will be very close to zero (Hensel and Hirsch, 2002).

Both exact and large sample approximation versions of the hypothesis test for Spearman's rho are presented by Bhattacharyya and Johnson (1977). The large sample approximation is only accurate for fairly large samples (n > 20). However, that is considered sufficient for this thesis, as all records are longer than ~40 years. The significance of ρ can be tested by determining whether ρ differs from zero. The test statistic t_ρ is calculated by

$$t_\rho = \frac{\rho\sqrt{n-2}}{\sqrt{1-\rho^2}} \tag{14}$$

The test statistic can be compared to a table of the t distribution with $n - 2$ degrees of freedom (Hensel and Hirsch, 2002). Corresponding p-values can also be computed ($p = 2[1 - \mathrm{F}(|t|)]$).

4.6 Selection of periods for trend and correlation analysis

As noted by Hirsch et al. (1991), the frequent problems of multiple starting and ending dates, and data gaps in a group of records, represent a significant practical problem in trend studies. In order to correctly interpret the data, the records examined in a multiple station study must be concurrent, i.e. they must have observations covering the same time period. It is less value to compare the trend over one period at one site, to the trend over another period at another site. Additionally, as shown by several studies (Duguay, 2006; Korhonen, 2006), the detected trends are very much dependent on which period is examined. By choosing different periods in records, different trends can be found.

As one of the main objectives of this thesis was to analyze temporal and regional trends in ice phenology across Norway, a decision was taken to examine both long-term trends and trends over fixed 30-year periods, similar to Hisdal et al. (2001) and Duguay et al. (2006). In addition, the temporal changes of trends in ice phenology and hydro-meteorological variables were examined at selected sites by computing the trend of moving 30-year periods. Based on this, the following approaches were taken in the trend and correlation analyses:

(1) Trends in ice phenology were computed for the *entire data period* for each ice observation site, similar to Magnuson et al. (2000) and Hodgkins et al. (2002). Correlation with hydro-meteorological variables (air temperature and discharge) was computed for the same time periods, unless for some reason relevant data could not be obtained. In such cases the longest period with overlapping meteorological data was used.

(2) Trends in ice phenology were computed for *fixed 30-year periods*. The use of longer periods (for example 50 years) would generally have been preferred, but an inspection of the data showed that longer periods would considerably reduce the common observation period between sites. The respective periods were chosen to maximize the number of sites, and to get a correct representation of trends during the 20th Century across Norway. Three 30-year periods, i.e. 1913 – 1942, 1954 – 1983 and 1982 – 2011, were selected for the trend analysis. In addition, one longer period of 73 years (1922 – 94), recorded at 10 sites was also included for comparison purposes.

(3) Trends in ice phenology and hydro-meteorological variables in the strongest correlated month identified in point (1) were computed for *non-concurrent 30-year periods* covering the last 30 years of each ice record. Correlation between freeze-up/break-up and air temperature was shown to vary considerably, not only with the starting and ending dates, but also with the length of the period examined (Figure 29; Figure 30). For this reason it was decided to compare trends in ice phenology and hydro-meteorological variables over periods of equal length. However, that did not resolve problem of non-concurrent time periods.

(4) The regional patterns in trends of seasonal air temperature over the 1954 – 83 period were studied. Seasonal temperatures were used instead of the most strongly correlated months to attain comparable results for all sites.

(5) Trends in ice phenology and hydro-meteorological variables were computed for moving 30-year periods at eight selected sites. Two sites – one lake and one river – with long records and high data quality were selected from each geographical region.

4.7 Software

Both the Mann-Kendall test and the Theil-Sen slope estimates were performed using a Microsoft Excel® template, MAKESENS, developed by Salimi et al. (2002). Computations of rank correlation coefficients were done using a self-made template in Microsoft Excel®. Probability plots, the Anderson-Darling test as well as most of the time series plots were made using the MINITAB® statistical software package. The change point tests (Pettitt's test, SNHT, Buishand's test and Von Neumann's test) were performed using a Microsoft Excel® add-in known as XLSTAT. All maps were made with ArcGIS®, and the map data (N5000) were provided by Statens Kartverk.

5 Results

The results of the analyses are presented in the following order: First the results of the quality control and the subsequent homogeneity analyses are presented, and the ice records considered suitable for trend analyses introduced. Long-term trends and trends of fixed 30-year periods are then presented, followed by results of the correlation analyses between ice phenology and hydro-meteorological variables. Trends in hydro-meteorological variables and trends in moving 30-year periods for selected sites are prestented at the end of the chapter.

5.1 Quality control

The quality control resulted in the removal of 114 outliers from the 142 ice records selected for the initial analysis (Table 3). 28, 35 and 51 values were removed from freeze-up, break-up and ice cover duration records, respectively. Of the total number of data points, the expunged values accounted for 0.9 % (freeze-up), 1.1 % (break-up) and 1.8 % (ice cover duration). Five records were excluded from the subsequent analyses on the basis of too many missing values (> 15 %). These were: Lomnessjø (2.132) for break-up; Veitastrondsvatn (77.2) for ice cover duration; Lygne (24.13.13) for ice cover duration and Horgheim (103.4) for freeze-up and ice cover duration.

Table 10: Completeness (% of years with data) of ice records post quality control. The numbers denote the number of records within each class.

Variable	85 – 90 %	91 – 95 %	96 – 100 %
Freeze-up	5	13	28
Break-up	6	16	24
Ice cover duration	8	18	18

The median completeness of the remaining 137 records was 97 % for freeze-up, 96 % for break-up and 95 % for ice cover duration. 23 records were complete. Few records (Table 10) were less than 90 % complete. There were minor differences in the completeness of lakes and river ice records. A summary of the data completeness for all records can be found in Appendix C

5.2 Homogeneity testing

The homogeneity testing resulted in the classification of 25 records (Table 11) as either “doubtful” or “suspect”. The results displayed small variations between lake and river sites and between regulated and unregulated sites. On average, slightly more homogeneity breaks were detected in river ice records than in lakes. Regulated and unregulated sites showed minor differences in the number of records classified as "useful".

Table 11: Results of homogeneity test applied to all variables. Test results were classified as "useful", "doubtful" or "suspect" based on the criterions put forward in section 4.3.1.

Variable	Class 1 "useful"	Class 2 "doubtful"	Class 3 "suspect"
Freeze-up	38 (83 %)	2 (4 %)	6 (13 %)
Break-up	38 (81 %)	3 (6 %)	6 (13 %)
Ice cover duration	36 (82 %)	3 (7 %)	5 (11 %)

For the sake of consistency, all records classified as "suspect" were excluded from the subsequent analyses. Records classified as "doubtful" were also excluded, with three exceptions; break-up dates for Veitastrondsvatn (77.2) and Lygne (24.13.13), and the ice cover duration from Stai (2.117) were included, as these records were clearly non-normal, and thus not really suitable for application of parametric tests, as described in section 4.3.1. The Pettitt test did not detect breaks in any of these records.

Additionally, six records were found homogenous in the period following the detected year of break. Aursunden was found homogenous for freeze-up and ice cover duration post-1935 and break-up post-1962. Krøderen was found homogenous for freeze-up and ice cover duration post-1925. Femundsenden was found homogenous for freeze-up dates post-1946. Complete results of the homogeneity tests are can be found in Appendix D.

5.3 Ice records selected for trend analysis

A total of 119 records (Table 12) were selected for the trend analysis from the initial 142 records. These records were divided into three categories: (i) 41 that contained freeze-up dates; (ii) 40 that contained break-up dates; and (iii) 38 that contained the total duration of ice cover. Available metadata for the selected sites are located in Appendix A.

Table 12: Ice records selected for trend analysis. Blank cells indicate that the record was excluded from the analysis, either as a result of the quality control (>15 % of data missing) or because the record was classified as inhomogenous.

				Location			Freeze-up		Break-up		Ice cover duration	
		Station number	Station name	N	E	Elev. (MASL)	Period of record	Years of record	Period of record	Years of record	Period of record	Years of record
Lake sites	Regulated	2.375.1	Aursjø	61.9	8.3	1 098	1968 – 2011	44	1968 – 2011	44	1968 – 2011	44
		12.127	Bergsjø	60.7	8.3	1 082	1954 – 2003	49	1953 – 2002	50	1954 – 2001	48
		2.162	Bygdin	61.3	8.8	1 058	1968 – 2011	43	1968 – 2011	43	1968 – 2011	42
		2.167	Vinsteren	61.4	9.1	1 032	1951 – 2012	61	1951 – 2012	56	1951 – 2012	56
		2.15	Breiddalsvatn	62.0	7.6	900	1951 – 2012	62	1951 – 2012	60	1951 – 2012	60
		2.79	Tessevatn	61.8	8.9	854	1946 – 2012	60				
		15.9	Tunhovdfjord	60.3	8.9	734	1921 – 1994	71	1920 – 1994	68	1921 – 1994	66
		2.111	Aursunden	62.7	11.5	690	1935 – 2011	75	1962 – 2011	49	1935 – 2011	73
		12.87	Øyangen	61.2	8.9	677	1920 – 1985	62	1920 – 1984	65	1920 – 1984	61
		139.5	Namsvatn	65.0	13.6	454			1909 – 1968	57	1909 – 1968	57
		2.82	Osensjøen	61.2	11.7	438	1968 – 2011	42			1968 – 2011	42
		12.89	Volbufjord	61.1	9.1	434	1920 – 1975	56	1920 – 1975	56	1920 – 1975	56
		2.132	Lomnessjø	61.7	11.2	256	1930 – 1972	43				
		2.14	Storsjø	61.4	11.4	251	1943 – 2011	65			1943 – 2011	62
		23.2	Færåsen	58.2	7.3	232	1952 – 2000	49	1952 – 1998	46	1952 – 1998	46
		77.2	Veitastrondsvatn	61.4	7.1	170	1919 – 1991	62	1922 – 1991	65		
		16.32	Hjartsjø	59.6	8.8	157	1920 – 1998	70	1919 – 1998	74	1920 – 1998	67
		12.98	Krøderen	60.1	9.8	132	1925 – 1964	38	1900 – 1964	63	1925 – 1964	38
		2.825.39	Mjøsa (Kise-Kapp)	60.8	10.8	123	1865 – 2013	140	1865 – 2013	142	1865 – 2013	140
		72.7	Vassbygdvatn	60.9	7.3	54	1916 – 1987	68	1915 – 1987	69	1916 – 1987	66
		62.5	Bulken (Vangsvatnet)	60.6	6.3	47	1902 – 1990	78	1925 – 1990	61	1925 – 1990	57
	Unregulated	2.131	Atnsjø	61.9	10.2	701	1918 – 1999	77	1954 – 1998	44	1954 – 1998	44
		311.4	Femundsenden	61.9	11.9	662	1946 – 1981	35	1901 – 1980	78		
		311.7	Engeren	61.5	12.1	472	1912 – 1983	70	1911 – 1983	70	1912 – 1983	67
		80.1	Rørvikvatn	61.2	5.8	336	1951 – 1998	48	1951 – 1997	47	1951 – 1997	47
		307.5	Murusjø	64.5	14.0	312	1931 – 2002	66			1950 – 2001	45
		24.13.13	Lygne (sørenden)	58.4	7.2	185	1926 – 2009	74	1924 – 2009	75		

		83.2	Hestadfjorden	61.3	5.9	146	1915 – 1996	79	1915 – 1995	71	1915 – 1995	71
		314.3	Rømsjø	59.7	11.8	138	1946 – 1996	48	1945 – 1995	47	1950 – 1995	46
		82.1	Nautsundvatn	61.3	5.4	47	1909 – 1983	75	1926 – 1983	55	1926 – 1983	55
		167.3	Kobbvatn	67.6	16.0	8	1917 – 1978	60	1917 – 1978	61	1917 – 1978	60
River sites	Regulated	26.5	Dorgefoss	58.9	6.8	465			1913 – 1981	62		
		73.1	Lo Bru	61.1	7.8	403			1917 – 1968	50	1918 – 1968	48
		2.117	Stai	61.5	11.1	256	1905 – 1999	93			1905 – 1998	92
		2.2	Nor	60.3	12.0	148	1901 – 1983	83	1911 – 1983	69	1911 – 1983	69
		122.2	Haga Bru	63.1	10.3	62	1909 – 1995	85	1913 – 1995	77	1913 – 1995	76
		103.4	Horgheim	62.5	7.8	55			1913 – 1983	62		
		22.4	Kjølemo	58.1	7.5	40	1901 – 1965	65	1900 – 1964	63	1901 – 1964	62
		246.1	Bjørnvatn	69.5	30.1	20			1913 – 1967	54		
		15.18	Bommestad bru	59.1	10.1	5	1901 – 1956	52	1900 – 1958	57	1901 – 1956	52
	Unregulated	12.70	Etna	61.0	9.6	400	1922 – 1997	75			1922 – 1996	70
		311.6	Nybergsund	61.3	12.3	360	1914 – 1974	61	1909 – 1973	59	1915 – 1973	56
		22.5	Austerhus	58.6	7.4	261	1923 – 1961	38	1923 – 1961	37	1923 – 1961	36
		15.20	Jondalselv	59.7	9.6	180	1920 – 1994	70	1920 – 1994	75	1920 – 1994	70
		196.35	Malangsfoss	69.0	18.7	30			1908 – 1966	59		
		212.2	Stengelsen	69.9	23.3	23	1916 – 1975	56	1916 – 1975	58	1916 – 1975	56
		234.1	Polmak	70.1	28.1	20	1912 – 1998	84	1912 – 1997	84	1912 – 1997	82

5.4 Trends in ice phenology

As noted in Section 4.6, trends in freeze-up dates, break-up dates and the total duration of ice cover were computed for: (i) The entire data period (i.e. long-term) for each station; and (ii) for fixed 30-year periods.

5.4.1 Long-term trends

Long-term trends in freeze-up dates, break-up dates and ice cover duration for each station for the entire data period are shown in Table 13, Table 14 to Table 15. Given the vastly different time periods, the results should not be compared directly between sites.

For lakes and rivers that lacked complete ice cover in some years, three different methods were used for the quantification of the no-ice years (se section 4.1.2). The results of the main method are displayed in the tables, whereas the alternative methods are presented as footnotes. The alternative methods resulted in slight to large differences in trends of freeze-up and break-up, depending on the method. Leaving out years without complete ice cover resulted in less positive freeze-up trends and more positive break-up trends compared to the other methods. Substituting no-ice years with the latest freeze-up and earliest break-up dates gave a trend almost identical to that of the main method. Hence, all subsequent analyses were conducted with the freeze-up and break-up dates for no-ice years inferred using the method of Assel and Robertson (1995).

Freeze-up dates

A positive trend indicating later freeze-up was found for 23 records. 18 records displayed a negative trend, pointing to earlier freeze-up. Four records exhibited significant positive trends at the 5 % level, while no records showed significant negative trends. The detected trends varied from $z = 3.30$ at Mjøsa to $z = -1.95$ at Femundsenden, with a median for all records of $z = 0.23$. The magnitude of the trend ranged from 5.3 days/decade at Bygdin to –4.3 days/decade at Femundsenden.

Break-up dates

A positive trend indicating later break-up was found for 14 records. 26 records displayed a negative trend, pointing to earlier break-up. Five records exhibited significant negative trends at the 5 % level, while no records showed significant positive trends. The detected trends varied from $z = 1.73$ at Dorgefoss to $z = -2.61$ at Bjørnvatn, with a median for all records of $z = -0.72$. The magnitude of the trend ranged from 3.8 days/decade at Austerhus to –2.1 days/decade at Bjørnvatn.

Ice cover duration

A total of 12 records displayed positive trends in ice cover duration (i.e. longer duration), whereas 26 records showed negative trends (i.e. shorter duration). Eight records exhibited significant negative trends at the 5 % level, while only one record showed a significant positive trend at the 5 % level. The detected trends varied from $z = 1.42$ at Austerhus to $z = -2.89$ at Namsvatn, with a median for all records of $z = -0.49$. The magnitude of the trend ranged from 7.1 days/decade at Austerhus to –6.1 days/decade at Lo bru.

Table 13: Long-term trends in freeze-up dates.

		Station number	Station name	Period of record	Years of record	z-score	p-value	Sen's slope (days/ decade)
Lake sites	Regulated	2.375.1	Aursjø	1968 – 2011	44	1.84	0.066	2.1
		12.127	Bergsjø	1954 – 2003	49	−0.07	0.944	0.0
		2.162	Bygdin	1968 – 2011	43	1.97	0.049	5.3
		2.167	Vinsteren	1951 – 2012	61	0.28	0.779	0.0
		2.15	Breiddalsvatn	1951 – 2012	62	−0.93	0.352	−0.8
		2.79	Tessevatn	1946 – 2012	60	2.35	0.019	2.2
		15.9	Tunhovdfjord	1921 – 1994	71	−1.18	0.238	−0.8
		2.111	Aursunden	1935 – 2011	75	0.80	0.423	0.3
		12.87	Øyangen	1920 – 1985	62	0.23	0.818	0.0
		2.82	Osensjøen	1968 – 2011	42	1.00	0.317	2.4
		12.89	Volbufjord	1920 – 1975	56	−0.01	0.992	0.0
		2.132	Lomnessjø	1930 – 1972	43	−0.40	0.689	−0.7
		2.14	Storsjø[1]	1943 – 2011	65	0.42	0.674	0.6
		23.2	Færåsen	1952 – 2000	49	−0.81	0.418	−1.0
		77.2	Veitastrondsvatn[2]	1919 – 1991	62	1.80	0.072	2.0
		16.32	Hjartsjø	1920 – 1998	70	2.62	0.009	1.9
		12.98	Krøderen	1925 – 1964	38	−0.13	0.900	0.5
		2.825.39	Mjøsa (Kise-Kapp)[3]	1865 – 2013	140	3.30	0.001	1.2
		72.7	Vassbygdvatn[4]	1916 – 1987	68	−0.59	0.555	−0.8
		62.5	Bulken (Vangsvatnet)	1902 – 1990	78	−0.09	0.928	0.0
	Unregulated	2.131	Atnsjø	1918 – 1999	77	0.86	0.390	0.4
		311.4	Femundsenden	1946 – 1981	35	−1.95	0.051	−4.3
		311.7	Engeren	1912 – 1983	70	−1.51	0.131	−1.1
		80.1	Rørvikvatn	1951 – 1998	48	−0.54	0.589	−1.1
		307.5	Murusjø	1931 – 2002	66	0.26	0.795	0.0
		24.13.13	Lygne (sørenden)[5]	1926 – 2009	74	1.75	0.080	1.7
		83.2	Hestadfjorden[6]	1915 – 1996	79	−0.80	0.424	−0.9
		314.3	Rømsjø	1946 – 1996	48	−0.25	0.803	−0.5
		82.1	Nautsundvatn	1909 – 1983	75	−0.14	0.889	0.0
		167.3	Kobbvatn	1917 – 1978	60	0.08	0.936	0.0
River sites	Regulated	2.117	Stai	1905 – 1999	93	−1.06	0.289	−0.5
		2.2	Nor	1901 – 1983	83	−0.42	0.674	−0.3
		122.2	Haga Bru	1909 – 1995	85	1.05	0.294	1.3
		22.4	Kjølemo[7]	1901 – 1965	65	1.55	0.121	2.6
		15.18	Bommestad bru	1901 – 1956	52	1.23	0.219	2.3
	Unregulated	12.70	Etna	1922 – 1997	75	0.40	0.689	0.2
		311.6	Nybergsund	1914 – 1974	61	0.33	0.741	0.2
		22.5	Austerhus[8]	1923 – 1961	38	−0.71	0.478	−2.9
		15.20	Jondalselv	1920 – 1994	70	0.61	0.542	0.7
		212.2	Stengelsen	1916 – 1975	56	0.22	0.826	0.0
		234.1	Polmak	1912 – 1998	84	0.83	0.407	0.5

[1] The record contained six years without complete ice cover. Dropping these years gave a trend in freeze-up dates of –0.3 days per decade with z = –0.31. Substituting with the latest freeze-up dates gave a trend in freeze-up dates of 0.5 days per decade with z = 0.39.

[2] The record contained one year without complete ice cover. Dropping this year gave a trend in freeze-up dates of 1.6 days per decade with $z = 1.48$. Substituting with the latest freeze-up dates gave a trend in freeze-up dates of 2.0 days per decade with $z = 1.79$.

[3] The record contained 34 years without complete ice cover. Dropping these years gave a trend in freeze-up dates of 1.4 days per decade with $z = 1.62$. Substituting with the latest freeze-up dates gave a trend in freeze-up dates of 1.5 days per decade with $z = 3.26$.

[4] The record contained two years without complete ice cover. Dropping these years gave a trend in freeze-up dates of –1.0 days per decade with $z = -0.70$. Substituting with the latest freeze-up dates gave a trend in freeze-up dates of –0.8 days per decade with $z = -0.58$.

[5] The record contained three years without complete ice cover. Dropping these years gave a trend in freeze-up dates of 1.1 days per decade with $z = 1.30$. Substituting with the latest freeze-up dates gave a trend in freeze-up dates of 1.6 days per decade with $z = 1.74$.

[6] The record contained two years without complete ice cover. Dropping these years gave a trend in freeze-up dates of –0.6 days per decade with $z = -0.59$. Substituting with the latest freeze-up dates gave a trend in freeze-up dates of –1.0 days per decade with $z = -0.89$.

[7] The record contained five years without complete ice cover. Dropping these years gave a trend in freeze-up dates of 2.4 days per decade with $z = 1.46$. Substituting with the latest freeze-up dates gave a trend in freeze-up dates of 2.6 days per decade with $z = 1.49$.

[8] The record contained four years without complete ice cover. Dropping these years gave a trend in freeze-up dates of –1.3 days per decade with $z = -0.30$. Substituting with the latest freeze-up dates gave a trend in freeze-up dates of –3.0 days per decade with $z = -0.76$.

Table 14: Long-term trends in break-up dates.

		Station number	Station name	Period of record	Years of record	z-score	p-value	Sen's slope (days/ decade)
Lake sites	Regulated	2.375.1	Aursjø	1968 – 2011	44	0.33	0.741	0.4
		12.127	Bergsjø	1953 – 2002	50	−0.61	0.542	−0.5
		2.162	Bygdin	1968 – 2011	43	0.46	0.646	0.0
		2.167	Vinsteren	1951 – 2012	56	0.32	0.749	0.0
		2.15	Breiddalsvatn	1951 – 2012	60	−0.72	0.472	−0.5
		15.9	Tunhovdfjord	1920 – 1994	68	−1.64	0.101	−0.7
		2.111	Aursunden	1962 – 2011	49	−2.05	0.040	−1.5
		12.87	Øyangen	1920 – 1984	65	1.07	0.285	0.6
		139.5	Namsvatn	1909 – 1968	57	−1.55	0.121	−1.1
		12.89	Volbufjord	1920 – 1975	56	−0.41	0.682	−0.2
		23.2	Færåsen	1952 – 1998	46	−0.84	0.401	−1.3
		77.2	Veitastrondsvatn[1]	1922 – 1991	65	−1.49	0.136	−0.8
		16.32	Hjartsjø	1919 – 1998	74	−0.90	0.368	−0.3
		12.98	Krøderen	1900 – 1964	63	−2.55	0.011	−1.9
		2.825.39	Mjøsa (Kise-Kapp)[2]	1865 – 2013	142	−1.49	0.135	−0.1
		72.7	Vassbygdvatn[3]	1915 – 1987	69	−0.12	0.904	0.0
		62.5	Bulken (Vangsvatnet)	1925 – 1990	61	0.01	0.992	0.0
	Unregulated	2.131	Atnsjø	1954 – 1998	44	−1.84	0.066	−1.2
		311.4	Femundsenden	1901 – 1980	78	−1.04	0.298	−0.5
		311.7	Engeren	1911 – 1983	70	−0.92	0.358	−0.5
		80.1	Rørvikvatn	1951 – 1997	47	0.01	0.992	0.0
		24.13.13	Lygne (sørenden)[4]	1924 – 2009	75	−0.07	0.944	0.0
		83.2	Hestadfjorden[5]	1915 – 1995	71	−0.71	0.478	−0.6
		314.3	Rømsjø	1945 – 1995	47	−1.08	0.280	−1.6
		82.1	Nautsundvatn	1926 – 1983	55	0.53	0.596	0.9
		167.3	Kobbvatn	1917 – 1978	61	1.26	0.208	0.8
River sites	Regulated	26.5	Dorgefoss	1913 – 1981	62	1.73	0.084	1.4
		73.1	Lo Bru	1917 – 1968	50	0.45	0.653	0.6
		2.2	Nor	1911 – 1983	69	−0.50	0.617	−0.3
		122.2	Haga Bru	1913 – 1995	77	−1.10	0.271	−0.6
		103.4	Horgheim	1913 – 1983	62	0.23	0.818	0.2
		22.4	Kjølemo[6]	1900 – 1964	63	1.12	0.263	1.8
		246.1	Bjørnvatn	1913 – 1967	54	−2.61	0.009	−2.1
		15.18	Bommestad bru	1900 – 1958	57	0.19	0.849	0.1
	Unregulated	311.6	Nybergsund	1909 – 1973	59	−1.19	0.234	−0.7
		22.5	Austerhus[7]	1923 – 1961	37	1.10	0.271	3.8
		15.20	Jondalselv	1920 – 1994	75	−1.23	0.219	−1.1
		196.35	Malangsfoss	1908 – 1966	59	−1.06	0.289	−0.7
		212.2	Stengelsen	1916 – 1975	58	−0.16	0.873	0.0
		234.1	Polmak	1912 – 1997	84	−1.50	0.134	−0.5

[1] The record contained one year without complete ice cover. Dropping this year gave a trend in break-up dates of –0.8 days per decade with z = –1.17. Substituting with the earliest break-up dates gave a trend in break-up dates of –0.8 days per decade with z = –1.49.

[2] The record contained 34 years without complete ice cover. Dropping these years gave a trend in break-up dates of 0.4 days per decade with z = 0.20. Substituting with the earliest break-up dates gave a trend in break-up dates of –0.5 days per decade with z = –2.10.

[3] The record contained two years without complete ice cover. Dropping these years gave a trend in break-up dates of 0.0 days per decade with $z = -0.03$. Substituting with the earliest break-up dates gave a trend in break-up dates of –0.0 days per decade with $z = -0.12$.

[4] The record contained three years without complete ice cover. Dropping these years gave a trend in break-up dates of 0.3 days per decade with $z = 0.42$. Substituting with the earliest break-up dates gave a trend in break-up dates of 0.0 days per decade with $z = -0.09$.

[5] The record contained two years without complete ice cover. Dropping these years gave a trend in break-up dates of –0.8 days per decade with $z = -1.04$. Substituting with the earliest break-up dates gave a trend in break-up dates of –0.6 days per decade with $z = -0.68$.

[6] The record contained five years without complete ice cover. Dropping these years gave a trend in break-up dates of 1.6 days per decade with $z = 0.99$. Substituting with the earliest break-up dates gave a trend in break-up dates of 1.8 days per decade with $z = 1.12$.

[7] The record contained four years without complete ice cover. Dropping these years gave a trend in break-up dates of 2.2 days per decade with $z = 0.65$. Substituting with the earliest break-up dates gave a trend in break-up dates of 4.2 days per decade with $z = 1.15$.

Table 15: Long-term trends in ice cover duration.

		Station number	Station name	Period of record	Years of record	z-score	p-value	Sen's slope (days/ decade)
Lake sites	Regulated	2.375.1	Aursjø	1968 – 2011	44	−0.85	0.395	−1.8
		12.127	Bergsjø	1954 – 2001	48	0.50	0.617	0.6
		2.162	Bygdin	1968 – 2011	42	−2.39	0.017	−5.9
		2.167	Vinsteren	1951 – 2012	56	−1.02	0.308	−1.0
		2.15	Breiddalsvatn	1951 – 2012	60	−1.28	0.201	−1.5
		15.9	Tunhovdfjord	1921 – 1994	66	0.14	0.889	0.0
		2.111	Aursunden	1935 – 2011	73	−2.45	0.014	−1.5
		12.87	Øyangen	1920 – 1984	61	0.16	0.873	0.0
		139.5	Namsvatn	1909 – 1968	57	−2.89	0.004	−4.3
		2.82	Osensjøen	1968 – 2011	42	−2.40	0.016	−5.0
		12.89	Volbufjord	1920 – 1975	56	−0.47	0.638	−0.5
		2.14	Storsjø	1943 – 2011	62	−0.65	0.516	−0.9
		23.2	Færåsen	1952 – 1998	46	−0.33	0.741	−1.3
		16.32	Hjartsjø	1920 – 1998	67	−2.14	0.032	−2.2
		12.98	Krøderen	1925 – 1964	38	−0.84	0.399	−2.5
		2.825.39	Mjøsa (Kise-Kapp)	1865 – 2013	140	−2.61	0.009	−1.3
		72.7	Vassbygdvatn	1916 – 1987	66	0.49	0.624	1.2
		62.5	Bulken (Vangsvatnet)	1925 – 1990	57	−0.49	0.624	−1.0
	Unregulated	2.131	Atnsjø	1954 – 1998	44	0.76	0.447	1.4
		311.7	Engeren	1912 – 1983	67	0.50	0.617	0.5
		80.1	Rørvikvatn	1951 – 1997	47	0.04	0.968	0.0
		307.5	Murusjø	1950 – 2001	45	−1.15	0.250	−1.7
		83.2	Hestadfjorden	1915 – 1995	71	−0.44	0.660	−0.8
		314.3	Rømsjø	1950 – 1995	46	−1.51	0.131	−5.0
		82.1	Nautsundvatn	1926 – 1983	55	1.23	0.219	3.3
		167.3	Kobbvatn	1917 – 1978	60	0.31	0.757	0.6
River sites	Regulated	73.1	Lo Bru	1918 – 1968	48	−2.47	0.013	−6.1
		2.117	Stai	1905 – 1998	92	−2.52	0.012	−1.4
		2.2	Nor	1911 – 1983	69	1.33	0.184	1.7
		122.2	Haga Bru	1913 – 1995	76	−0.29	0.771	−0.4
		22.4	Kjølemo	1901 – 1964	62	−0.02	0.984	0.0
		15.18	Bommestad bru	1901 – 1956	52	−1.28	0.201	−3.6
	Unregulated	12.70	Etna	1922 – 1996	70	−1.31	0.190	−1.3
		311.6	Nybergsund	1915 – 1973	56	−0.82	0.412	−1.2
		22.5	Austerhus	1923 – 1961	36	1.42	0.156	7.1
		15.20	Jondalselv	1920 – 1994	70	−1.47	0.141	−2.2
		212.2	Stengelsen	1916 – 1975	56	0.15	0.882	0.0
		234.1	Polmak	1912 – 1997	82	−1.42	0.156	−1.1

5.4.2 Fixed periods

The spatial distribution of trends in freeze-up, break-up and ice cover across Norway for the fixed 30-year periods 1914 – 1942, 1954 – 1982, 1982 – 2011 and the longer 1922 – 1994 period are shown in Figure 25 to Figure 28. For the sake of brevity, only maps have been included in the thesis. The 1954 – 83 period covered the highest number of sites with 29, whereas the longer 1922 – 94 period included only 10 sites.

Freeze-up dates

With a few exceptions, clear large-scale spatial patterns were difficult to discern in the trends, perhaps owing to the relatively large regional variability in climate, topography, run-off and lake depth. The results yielded only minor differences between regulated and unregulated sites, indicating that the homogeneity testing had removed any records that contained biases due to regulations.

- Trends during the 1913 to 1942 period appeared to be negative (i.e. earlier freeze-up) in Western Norway and largely positive (i.e. later freeze-up) in Trøndelag, Eastern and Northeastern Norway. Two sites displayed significant positive trends, while one site showed a significant negative trend at the 5 % level.

- Trends during the 1954 – 83 period displayed less spatial variation compared to the earlier two periods. For the most part, trends were negative in all regions, with the exception of some sites in Eastern and Western Norway. Three sites showed significant negative trends.

- Trends during the 1982 – 2011 period were largely positive, but none of the trends were significant. However, the period only included sites in northern parts of Eastern Norway and southern parts of Trøndelag (Aursunden) – a rather limited geographical area compared to the other periods.

- Trends during the 1922 – 94 period varied throughout Norway. Four sites displayed positive trends and five sites displayed negative trends, one of which was significant.

Some spatial patterns in changes from period to periods could also be observed. Trends appeared to be consistently negative in Western Norway during the first two 30-year periods and in the longer 1922 – 94 period. The trend was also negative in Southern Norway during the first two periods. Eastern and Northern Norway displayed no coherent changes from period to period and the pattern appeared to be random. However, it is difficult to drawn any firm conclusions from the changes between the periods, as the sites included in each period varies greatly.

Break-up dates

Somewhat similar to freeze-up dates, break-up dates also displayed limited spatial coherence in trends for most periods.

- Trends during the 1913 – 42 period varied considerably site-to-site, and no spatial patterns were evident. Two sites displayed significant positive trends at the 5 % level, while none displayed significant negative trends.

- Trends during the 1954 – 83 period exhibited considerable site-to-site variation, and varied from positive to negative, even at nearby sites. With some exception, trends appeared to be positive in Western Norway and central/western parts of Eastern Norway, while the rest of Norway displayed negative trends. None of the trends were significant at the 5 % level.

- Trends during the 1982 – 2011 period were largely negative, but none of the trends were significant. However, the period only included sites in northern parts of Eastern Norway and southern parts of Trøndelag (Aursunden) – a rather limited geographical area compared to the other periods.

- Trends during the 1922 – 1994 period were mostly negative throughout Norway, with the exception of Mjøsa, which displayed no trend at all. One site displayed a significant negative trend.

Some spatial patterns in changes from period to periods could also be observed. Trends in break-up appeared to be negative in negative over eastern parts of Eastern Norway during the all 30-year periods and in the longer 1922 – 94 period. For other regions the changes did not appear to be coherent. However, it is difficult to drawn any firm conclusions from the changes between the periods, as the sites included in each period varies greatly.

Ice cover duration

Much similar to both freeze-up and break-up dates, ice cover duration also displayed limited spatial coherence in trends for most periods.

- Trends during the 1913 – 42 period were positive at the most northerly and southerly locations (Polmak and Kjølemo), neutral at Bommestad bru and negative at all other sites in between. One site displayed a significant negative trend at the 5 % level.

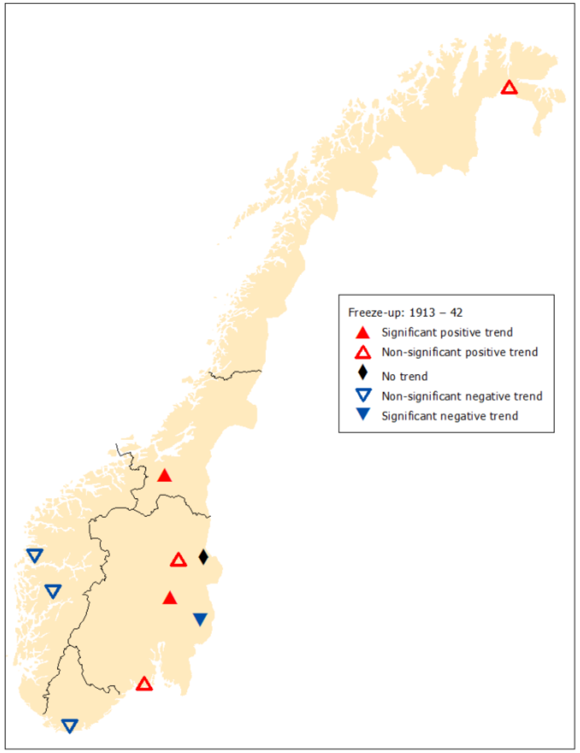
- Trends during the 1954 – 83 period exhibited considerable site-to-site variation, and varied from positive to negative, even at nearby sites. However, with a fair amount of exceptions, trends appeared to be positive over most of Norway. Two sites displayed significant positive trends.

- Trends during the 1982 – 2011 period were largely negative, but none of the trends were significant. However, the period only included sites in northern parts of Eastern Norway and southern parts of Trøndelag (Aursunden) – a rather limited geographical area compared to the other periods.

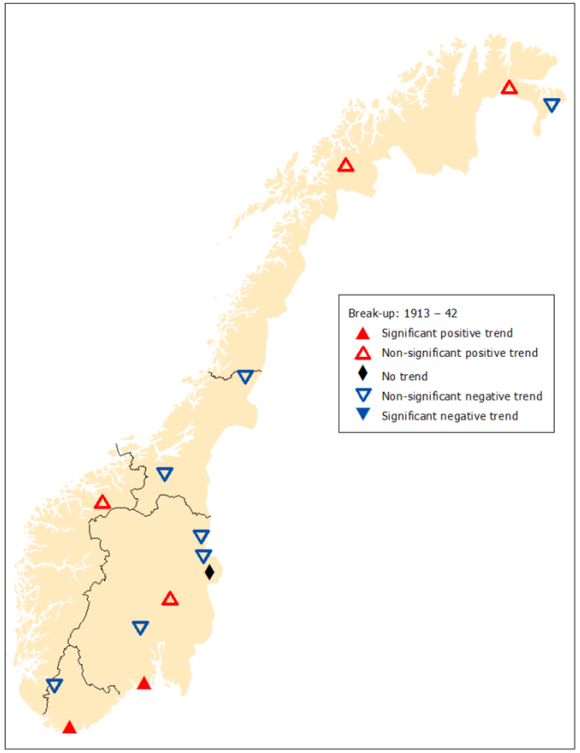
- Trends during the 1922 – 1994 period varied somewhat throughout Norway. Three sites displayed positive trends, five sites displayed negative trends, while one site exhibited no trend at all. Only one site displayed a significant (negative) trend.

Some spatial patterns in changes from period to periods could also be observed. Trends in break-up appeared to be negative in southern Trøndelag and over eastern parts of Eastern Norway during the all 30-year periods. Other regions displayed few/no coherent changes from period to period. However, it is difficult to drawn any firm conclusions from the changes between the periods, as the sites included in each period varies greatly.

(a)



(b)



(c)

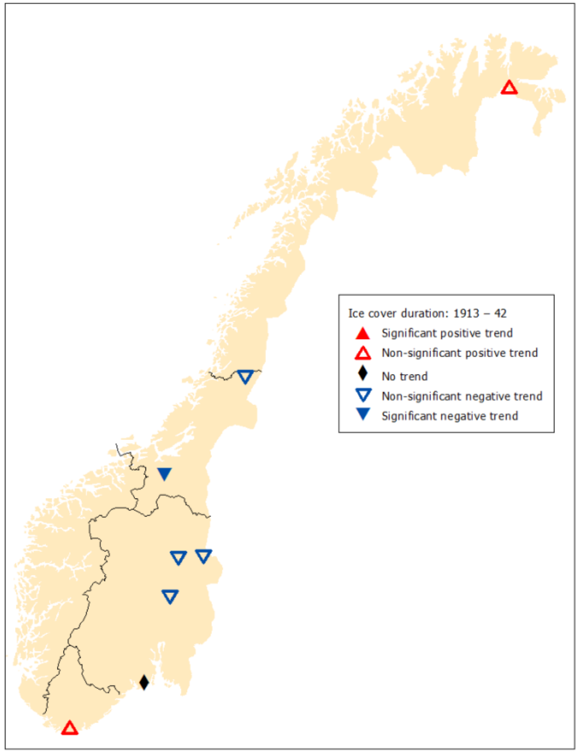


Figure 25: Trends in (a) freeze-up dates, (b) break-up dates and (c) total duration of ice cover across Norway for period 1913 – 42. Triangles pointing up indicate later freeze-up/break-up dates and longer duration of ice cover, while those pointing down indicate earlier freeze-up/break-up dates and shorter duration of ice cover. Sites with significant trends at the 5 % ($Z > |1.96|$) level are denoted by filled triangles. The cut-off point for "No trend" is defined as $Z < |0.20|$.

(a) (b) (c)

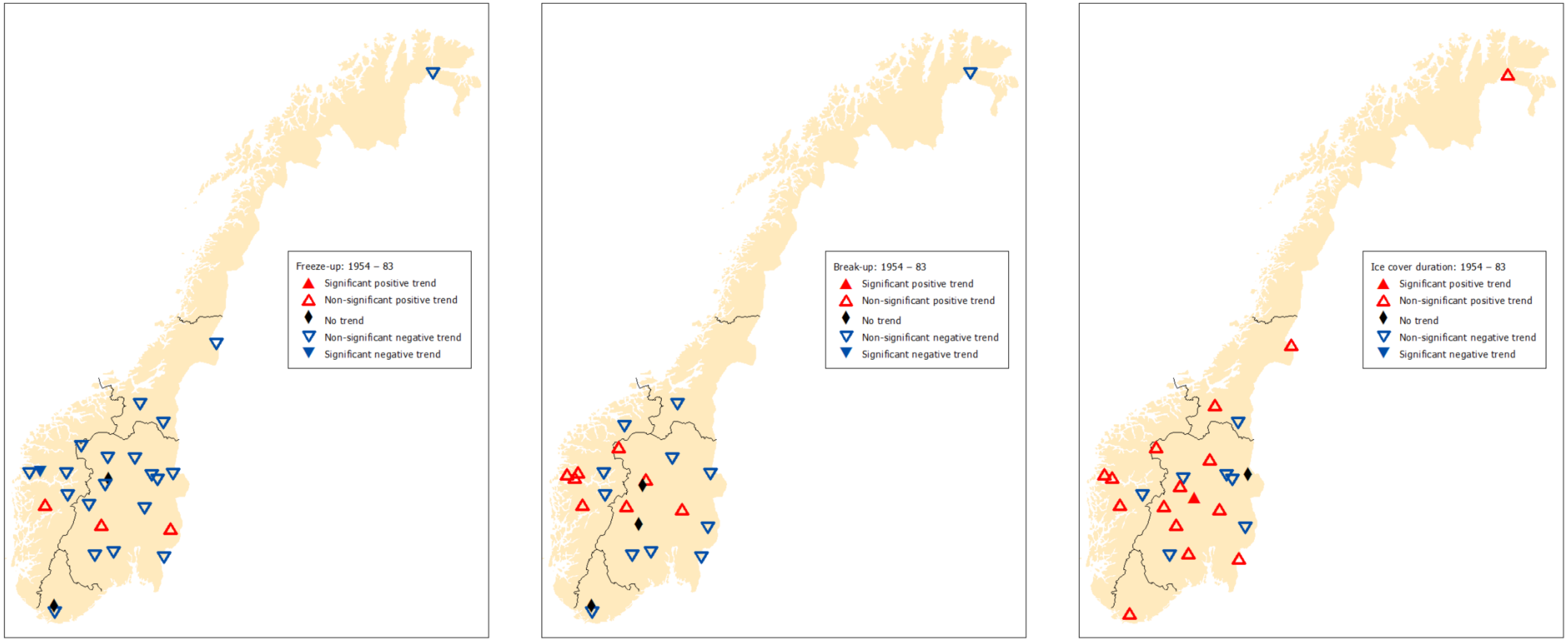


Figure 26: Trends in (a) freeze-up dates, (b) break-up dates and (c) total duration of ice cover across Norway for period 1954 – 83. Triangles pointing up indicate later freeze-up/break-up dates and longer duration of ice cover, while those pointing down indicate earlier freeze-up/break-up dates and shorter duration of ice cover. Sites with significant trends at the 5 % ($Z > |1.96|$) level are denoted by filled triangles. The cut-off point for "No trend" is defined as $Z < |0.20|$.

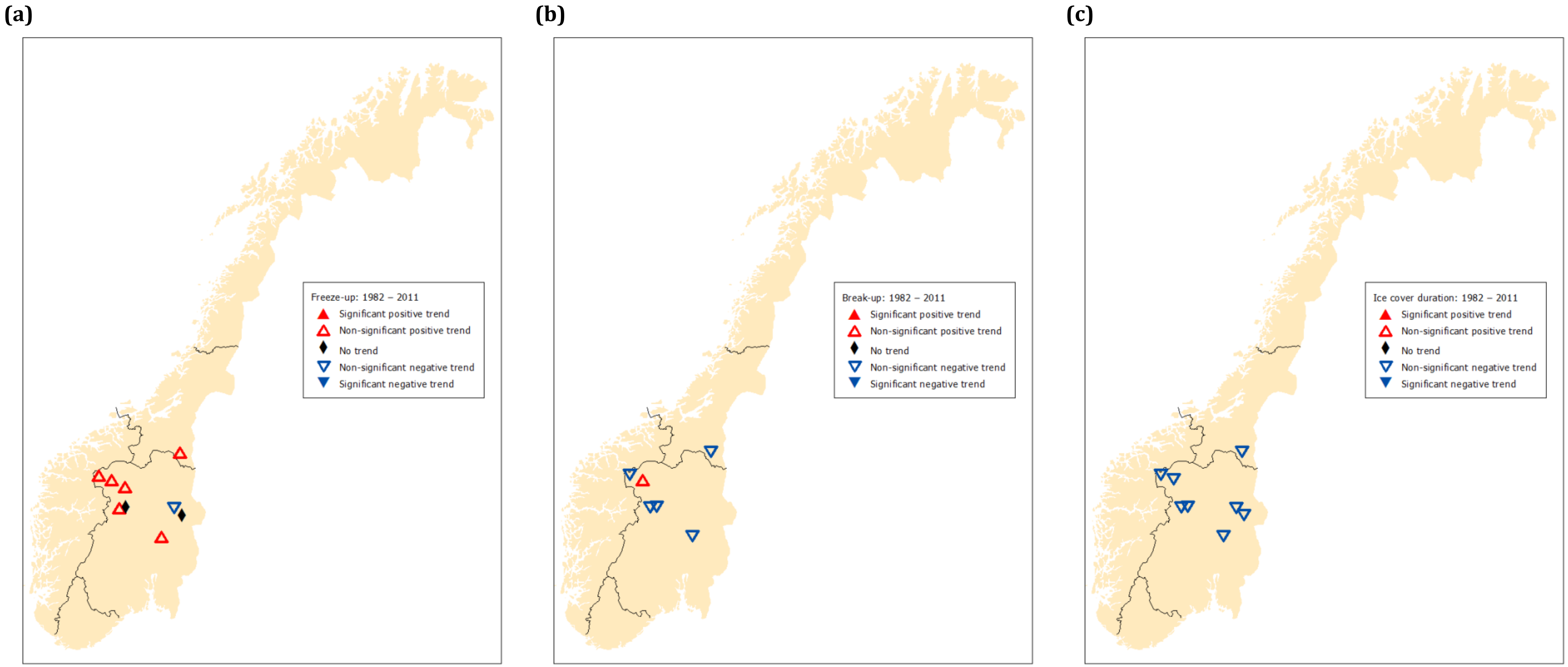


Figure 27: Trends in (a) freeze-up dates, (b) break-up dates and (c) total duration of ice cover across Norway for period 1982 – 2011. Triangles pointing up indicate later freeze-up/break-up dates and longer duration of ice cover, while those pointing down indicate earlier freeze-up/break-up dates and shorter duration of ice cover. Sites with significant trends at the 5 % ($Z > |1.96|$) level are denoted by filled triangles. The cut-off point for "No trend" is defined as $Z < |0.20|$.

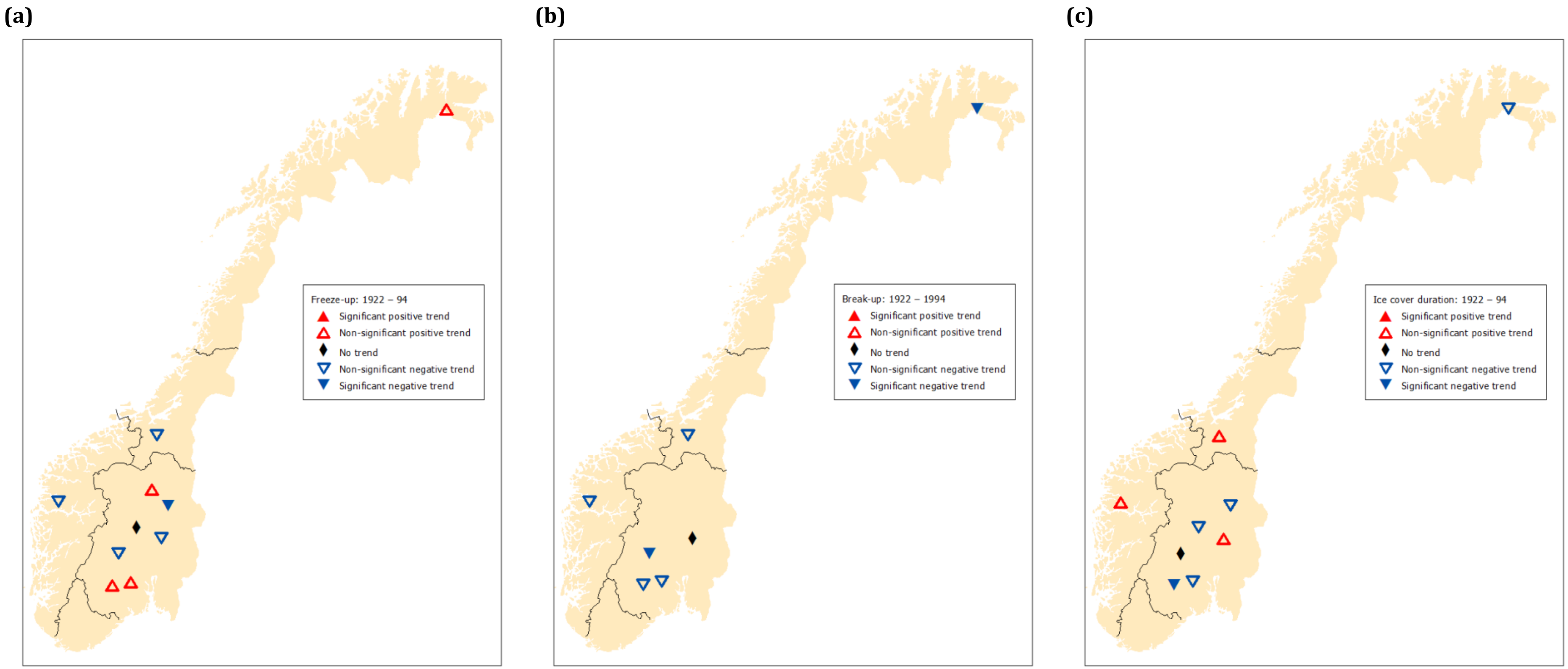


Figure 28: Trends in (a) freeze-up dates, (b) break-up dates and (c) total duration of ice cover across Norway for period 1922 – 94. Triangles pointing up indicate later freeze-up/break-up dates and longer duration of ice cover, while those pointing down indicate earlier freeze-up/break-up dates and shorter duration of ice cover. Sites with significant trends at the 5 % ($Z > |1.96|$) level are denoted by filled triangles. The cut-off point for "No trend" is defined as $Z < |0.20|$.

5.5 Links with hydro-meteorological variables

5.5.1 Monthly air temperature

The results showed that freeze-up and break-up exhibited a moderate to strong correlation with autumn (September – November) and spring (March – May) air temperatures, respectively. The specific month that correlated most strongly with freeze-up and break-up was found to vary from site to site, mainly governed by site elevation and latitude. For the sake of brevity, only the monthly correlations have been included (Table 16; Table 17). It should be noted that the computed correlation coefficients are for the entire data period, not a concurrent period for all sites. The correlation coefficients for other (concurrent) periods are likely to be different.

In accordance with previous studies (Robertson et al., 1992; Palecki and Barry, 1986), freeze-up was found to correlate most strongly with air temperatures in the month of the event, or in the month preceding the event. Similarly, break-up was found to correlate best with air temperatures in the month of the event or in the month preceding the event. The correlation (coefficient) between freeze-up and break-up and air temperature was positive and negative, respectively. Hence, higher temperatures lead to later freeze-up and earlier break-up, and vice versa.

Lakes sites displayed slightly higher correlation than rivers between air temperature and freeze-up. The median correlation for lakes was 0.59 as opposed to 0.50 for rivers. For all sites the median correlation was 0.58, ranging from 0.84 at Osensjøen to 0.15 at Nautsundvatn. All correlations were significant at the 5 % level, with the exception of Nautsundvatn.

Rivers showed slightly higher correlation than lakes between air temperature and break-up. The difference however was minor, with median correlations of –0.69 for rivers and –0.64 for lakes. For all sites the median correlation was –0.66, ranging from –0.84 at Krøderen to –0.38 at Breiddalsvatn. All correlations were significant at the 5 %.

The temporal evolution of correlation between air temperature and freeze-up/break-up at Mjøsa (Kise-Kapp) is shown in Figure 29 and Figure 30. The correlation between freeze-up/break-up and air temperature is noticeably dependent on the start- and endpoints as well as the length of the period for which correlation is computed.

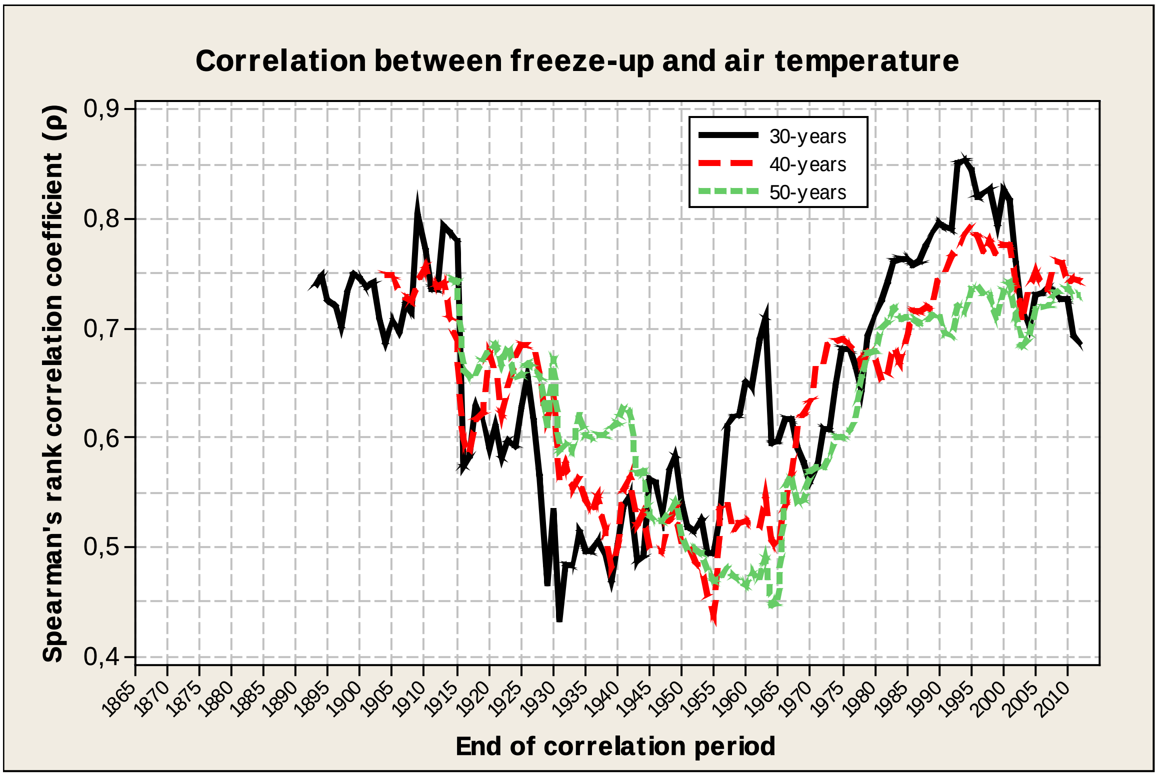


Figure 29: Temporal evolution of correlation between freeze-up at Mjøsa (Kise-Kapp) and air temperatures in January at Oslo (18700).

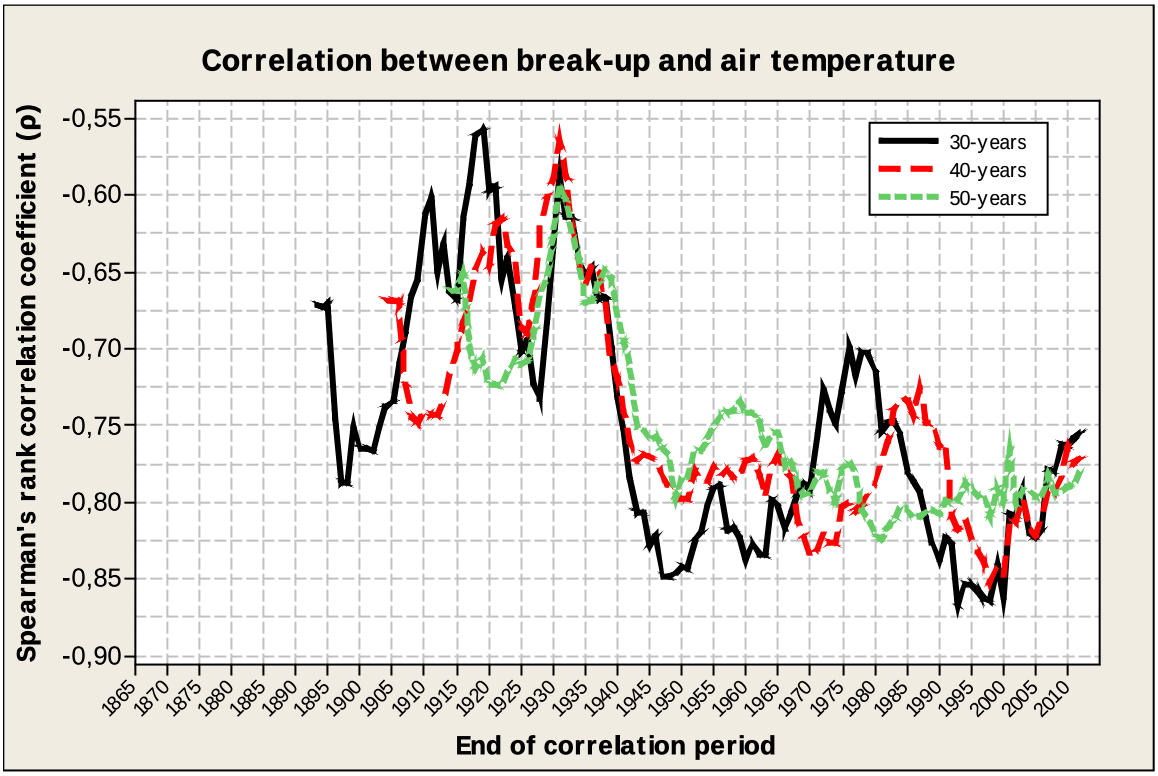


Figure 30: Temporal evolution of correlation between break-up dates at Mjøsa (Kise-Kapp) and air temperatures in February at Oslo (18700).

Table 16: Spearman's rank correlation coefficients between freeze-up dates and air temperature.

		Station number	Station name	Met.no station	Period of correlation	Median freeze-up date	Most strongly correlated month	Spearman's ρ	p-value
Lake sites	Regulated	2.375.1	Aursjø	Fokstugu (16610)	1967 – 2010	5. November	October	0.55	<0.001
		12.127	Bergsjø	Dagali (29720)	1953 – 2002	10. November	October	0.51	<0.001
		2.162	Bygdin	Skåbu (13670)	1968 – 2009	5. January	December	0.68	<0.001
		2.167	Vinsteren	Fokstugu (16610)	1950 – 2011	12. November	November	0.52	<0.001
		2.15	Breiddalsvatn	Fokstugu (16610)	1950 – 2011	23. November	November	0.66	<0.001
		2.79	Tessevatn	Fokstugu (16610)	1945 – 2011	20. November	November	0.68	<0.001
		15.9	Tunhovdfjord	Dagali (29720)	1920 – 1993	1. December	November	0.50	<0.001
		2.111	Aursunden	Røros (10380)	1935 – 2010	20. November	November	0.69	<0.001
		12.87	Øyangen	Åbjørsbråten (23160)	1924 – 1984	17. November	November	0.59	<0.001
		2.82	Osensjøen	Rena (7010)	1967 – 2010	26. December	December	0.84	<0.001
		12.89	Volbufjord	Åbjørsbråten (23160)	1924 – 1974	20. November	November	0.67	<0.001
		2.132	Lomnessjø	Rena (7010)	1929 – 1971	21. November	October	0.37	0.017
		2.14	Storsjø	Rena (7010)	1943 – 2011	28. January	January	0.72	<0.001
		23.2	Færåsen	Byglandsfjord (39690)	1951 – 1999	12. December	November	0.55	<0.001
		77.2	Veitastrondsvatn	Fjærland (55820)	1921 – 1990	22. December	December	0.63	<0.001
		16.32	Hjartsjø	Gvarv (32060)	1919 – 1994	30.November	November	0.51	<0.001
		12.98	Krøderen	Nesbyen (24890)	1925 – 1964	8. December	November	0.39	0.018
		2.825.39	Mjøsa (Kise-Kapp)	Oslo (18700)	1865 – 2013	5. February	January	0.65	<0.001
		72.7	Vassbygdvatn	Lærdal (54110)	1915 – 1986	7. January	December	0.69	<0.001
		62.5	Bulken (Vangsvatnet)	Voss (51530)	1935 – 1990	19. December	December	0.49	<0.001
	Unregulated	2.131	Atnsjø	Røros (10380)	1917 – 1998	22. November	November	0.49	<0.001
		311.4	Femundsenden	Røros (10380)	1946 – 1980	2. December	November	0.70	<0.001
		311.7	Engeren	Rena (7010)	1911 – 1982	16. December	December	0.57	<0.001
		80.1	Rørvikvatn	Takle (52860)	1950 – 1997	7. December	November	0.67	<0.001
		307.5	Murusjø	Nordli (73450)	1930 – 2001	2. December	November	0.55	<0.001
		24.13.13	Lygne (sørenden)	Byglandsfjord (39690)	1925 – 2008	29. December	December	0.67	<0.001
		83.2	Hestadfjorden	Vangsnes (53100)	1941 – 1994	7. January	December	0.41	0.004
		314.3	Rømsjø	Rygge (17150)	1945 – 1996	24. December	December	0.62	<0.001

		82.1	Nautsundvatn	Vangsnes (53100)	1941 – 1983	19. December	December	0.15	0.353
		167.3	Kobbvatn	Bodø (82290)	1921 – 1976	4. December	November	0.58	<0.001
River sites	Regulated	2.117	Stai	Rena (7010)	1904 – 1998	5. November	October	0.58	<0.001
		2.2	Nor	Flisa (6020)	1919 – 1982	24. November	November	0.59	<0.001
		122.2	Haga Bru	Selbu (68290)	1920 – 1994	7. December	December	0.47	<0.001
		22.4	Kjølemo	Mandal (41110)	1900 – 1964	30. December	December	0.58	<0.001
		15.18	Bommestad bru	Færder (27500)	1900 – 1950	9. December	November	0.76	<0.001
	Unregulated	12.70	Etna	Åbjørsbråten (23160)	1924 – 1996	19. November	November	0.48	<0.001
		311.6	Nybergsund	Rena (7010)	1913 – 1973	14. November	November	0.60	<0.001
		22.5	Austerhus	Byglandsfjord (39690)	1923 – 1961	10. January	December	0.68	<0.001
		15.20	Jondalselv	Kongsberg (28380)	1919 – 1993	28. November	November	0.52	<0.001
		212.2	Stengelsen	Alta (93140)	1915 – 1974	25. November	November	0.42	0.002
		234.1	Polmak	Karasjok (97251)	1911 – 1997	30. October	October	0.71	<0.001

Table 17: Spearman's rank correlation coefficients between break-up dates and air temperature.

		Station number	Station name	Met.no station	Period of correlation	Median break-up date	Most strongly correlated month	Spearman's ρ	p-value
Lake sites	Regulated	2.375.1	Aursjø	Fokstugu (16610)	1968 – 2011	18. June	May	−0.40	0.008
		12.127	Bergsjø	Dagali (29720)	1953 – 2002	9. June	May	−0.72	<0.001
		2.162	Bygdin	Skåbu (13670)	1969 – 2009	19. June	May	−0.48	0.002
		2.167	Vinsteren	Fokstugu (16610)	1951 – 2011	12. June	May	−0.54	<0.001
		2.15	Breiddalsvatn	Fokstugu (16610)	1951 – 2011	17. June	June	−0.38	0.004
		15.9	Tunhovdfjord	Dagali (29720)	1920 – 1994	23. May	April	−0.45	<0.001
		2.111	Aursunden	Røros (10380)	1962 – 2011	29. May	May	−0.61	<0.001
		12.87	Øyangen	Åbjørsbråten (23160)	1923 – 1984	29. May	April	−0.66	<0.001
		139.5	Namsvatn	Nordli (73450)	1921 – 1968	12. June	May	−0.78	<0.001
		12.89	Volbufjord	Åbjørsbråten (23160)	1923 – 1975	17. May	April	−0.63	<0.001
		23.2	Færåsen	Byglandsfjord (39690)	1952 – 1998	24. April	February	−0.83	<0.001
		77.2	Veitastrondsvatn	Fjærland (55820)	1922 – 1991	17. May	April	−0.60	<0.001

		16.32	Hjartsjø	Gvarv (32060)	1919 – 1994	1. May	March	−0.71	<0.001
		12.98	Krøderen	Nesbyen (24890)	1900 – 1964	3. May	April	−0.84	<0.001
		2.825.39	Mjøsa (Kise-Kapp)	Oslo (18700)	1865 – 2013	16. April	February	−0.75	<0.001
		72.7	Vassbygdvatn	Lærdal (54110)	1915 – 1987	23. April	February	−0.61	<0.001
		62.5	Bulken (Vangsvatnet)	Voss (51530)	1936 – 1990	23. April	March	−0.70	<0.001
	Unregulated	2.131	Atnsjø	Røros (10380)	1954 – 1998	27. May	May	−0.64	<0.001
		311.4	Femundsenden	Røros (10380)	1901 – 1980	27. May	May	−0.61	<0.001
		311.7	Engeren	Rena (7010)	1911 – 1983	19. May	April	−0.57	<0.001
		80.1	Rørvikvatn	Takle (52860)	1951 – 1997	17. May	April	−0.60	<0.001
		24.13.13	Lygne (sørenden)	Byglandsfjord (39690)	1924 – 2009	21. April	February	−0.68	<0.001
		83.2	Hestadfjorden	Vangsnes (53100)	1942 – 1994	27. April	March	−0.72	<0.001
		314.3	Rømsjø	Rygge (17150)	1945 – 1996	29. April	April	−0.72	<0.001
		82.1	Nautsundvatn	Vangsnes (53100)	1941 – 1983	16. April	March	−0.64	<0.001
		167.3	Kobbvatn	Bodø (82290)	1922 – 1977	29. May	May	−0.57	<0.001
River sites	Regulated	26.5	Dorgefoss	Tonstad (42810)	1920 – 1977	25. April	April	−0.74	<0.001
		73.1	Lo Bru	Lærdal (54110)	1917 – 1968	21. April	April	−0.57	<0.001
		2.2	Nor	Flisa (6020)	1920 – 1983	24. April	April	−0.66	<0.001
		122.2	Haga Bru	Selbu (68290)	1922 – 1995	19. April	March	−0.68	<0.001
		103.4	Horgheim	Sunndal (63500)	1912 – 1976	15. April	March	−0.68	<0.001
		22.4	Kjølemo	Mandal (41110)	1900 – 1964	22. March	March	−0.79	<0.001
		246.1	Bjørnvatn	Karasjok (97251)	1913 – 1967	31. May	May	−0.79	<0.001
		15.18	Bommestad bru	Færder (27500)	1900 – 1958	13. April	March	−0.71	<0.001
	Unregulated	311.6	Nybergsund	Rena (7010)	1909 – 1973	5. May	April	−0.78	<0.001
		22.5	Austerhus	Byglandsfjord (39690)	1923 – 1961	19. March	March	−0.69	<0.001
		15.20	Jondalselv	Kongsberg (28380)	1920 – 1994	17. April	April	−0.58	<0.001
		196.35	Malangsfoss	Dividalen (89950)	1922 – 1966	16. May	April/May	−0.56	<0.001
		212.2	Stengelsen	Alta (93140)	1916 – 1975	15. May	April	−0.49	<0.001
		234.1	Polmak	Karasjok (97251)	1912 – 1997	23. May	May	−0.70	<0.001

5.5.2 Monthly discharge (river sites)

Results showed that both freeze-up and break-up dates exhibited a strong correlation with discharge (Table 18; Table 19). Freeze-up was found to correlate most strongly with the discharge in the month of the freeze-up, or in the month before or after the freeze-up. Break-up was found to correlate most strongly with the discharge in the month of the break-up, or the month preceding the break-up. Correlation coefficients between freeze-up and break-up and discharge were positive and negative, respectively. Hence, higher discharges lead to later freeze-up and earlier break-up, and vice versa.

Break-up displayed stronger correlation with discharge than did freeze-up. The median correlation for freeze-up was 0.55, as opposed to −0.64 for break-up. Correlations between freeze-up and discharge ranged from 0.40 at Stengelsen to 0.63 at Austerhus and Jondalselv. Correlations between break-up and discharge ranged from −0.17 at Bommestad bru to −0.88 at Dorgefoss. All correlations were significant at the 5 % level, with the exception of break-up at Bommestad bru.

As with temperature, it should be noted that the computed correlation coefficients are for the entire data period, not a concurrent period for all sites. The correlation coefficients for other periods are likely to be different.

Table 18: Spearman's rank correlation coefficients between freeze-up dates and monthly discharge.

	Station number	Station name	Period of correlation	Median freeze-up date	Most strongly correlated month	Spearman's ρ	p-value
Regulated	2.117	Stai	1908 – 1998	5. November	November	0.48	<0.001
	2.2	Nor	1937 – 1982	24. November	December	0.55	<0.001
	122.2	Haga Bru	1909 – 1994	7. December	November	0.48	<0.001
	22.4	Kjølemo	1900 – 1964	30. December	December	0.54	<0.001
	15.18	Bommestad bru	1900 – 1926	9. December	December	0.60	0.001
Unregulated	12.70	Etna	1921 – 1996	19. November	November	0.51	<0.001
	311.6	Nybergsund	1913 – 1973	14. November	December	0.50	<0.001
	22.5	Austerhus	1922 – 1960	10. January	December	0.63	<0.001
	15.20	Jondalselv	1919 – 1993	28. November	December	0.63	<0.001
	212.2	Stengelsen	1915 – 1969	25. November	November	0.40	0.004
	234.1	Polmak	1911 – 1997	30. October	November	0.55	<0.001

Table 19: Spearman's rank correlation coefficients between break-up dates and monthly discharge.

	Station number	Station name	Period of correlation	Median break-up date	Most strongly correlated month	Spearman's ρ	p-value
Regulated	26.5	Dorgefoss	1914 – 1981	25. April	April	−0.88	<0.001
	73.1	Lo Bru	1917 – 1968	21. April	April	−0.60	<0.001
	2.2	Nor	1937 – 1983	24. April	April	−0.69	<0.001
	122.2	Haga Bru	1913 – 1995	19. April	March	−0.57	<0.001
	103.4	Horgheim	1913 – 1974	15. April	March	−0.60	<0.001
	22.4	Kjølemo	1900 – 1964	22. March	March	−0.70	<0.001
	246.1	Bjørnvatn	1913 – 1960	31. May	May	−0.66	<0.001
	15.18	Bommestad bru	1900 – 1926	13. April	April	−0.17	0.414
Unregulated	311.6	Nybergsund	1909 – 1973	5. May	April	−0.72	<0.001
	22.5	Austerhus	1923 – 1961	19. March	February	−0.64	<0.001
	15.20	Jondalselv	1920 – 1994	17. April	March	−0.51	<0.001
	196.35	Malangsfoss	1908 – 1966	16. May	May	−0.65	<0.001
	212.2	Stengelsen	1916 – 1969	15. May	May	−0.56	<0.001
	234.1	Polmak	1912 – 1997	23. May	May	−0.63	<0.001

5.6 Trends in hydro-meteorological variables

Trends in ice phenology and hydro-meteorological variables were computed for non-concurrent 30-year periods covering the last 30 years of each record. In addition, regional patterns in trends of seasonal air temperature over the 1954 – 83 period were studied. Furthermore, the temporal evolution of trends in ice phenology and hydro-meteorological variables were examined at selected sites by computing the trend of moving 30-year periods.

5.6.1 Non-concurrent 30-year periods

Trends in freeze-up, break-up, air temperature and discharge were computed for the best correlated months (Table 16; Table 17; Table 18; Table 19) all for sites. Correlation between freeze-up/break-up and air temperature was previously shown to vary considerably, not only with the starting and ending dates, but also with the length of the period examined (Figure 29; Figure 30). For the comparison of trends in these variables, 30-year periods were chosen, covering the last 30 years of each record. The time periods were not concurrent, but at least of equal length. The results (Table 20; Table 21) have been visualized using scatter plots (Figure 31; Figure 32) to ease the interpretation.

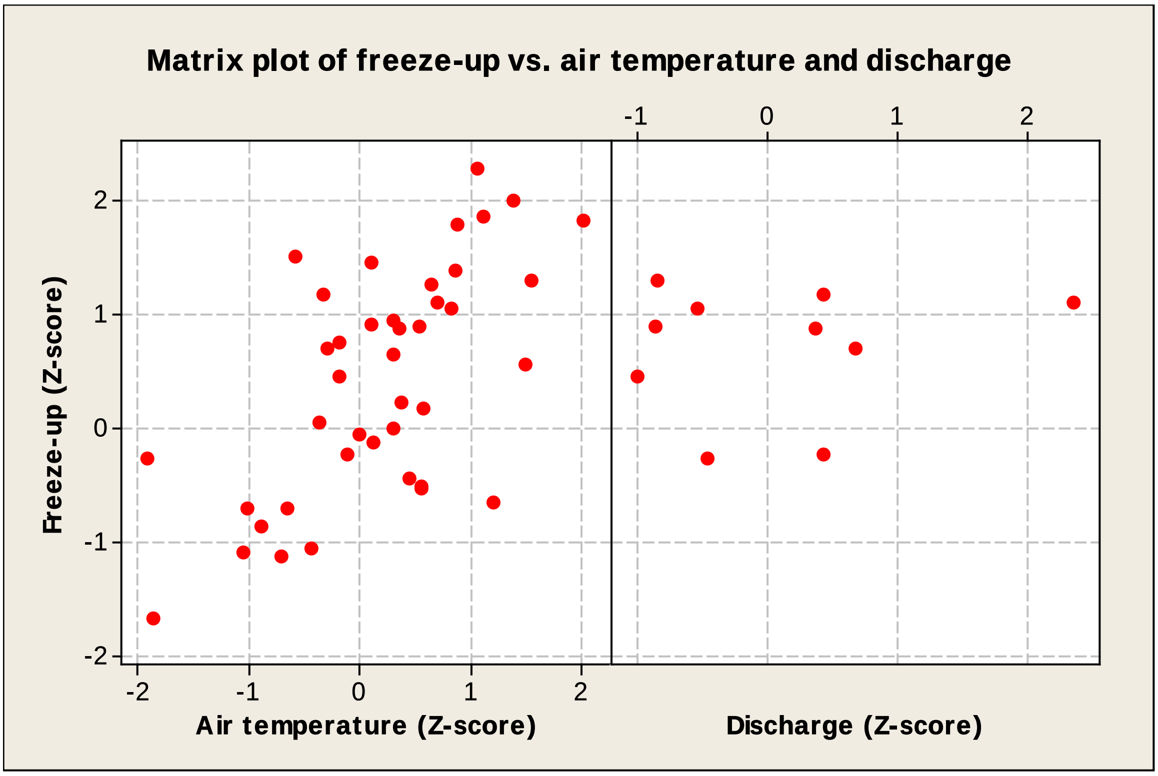


Figure 31: Scatter plots of trends (Z-scores) in freeze-up dates vs. trends in air temperature and discharge.

The results displayed at a clear relationship between trends in freeze-up and air temperature in the best correlated months. Positive trends in air temperature corresponded with positive trends in freeze-up, i.e. freeze-up occurred later in warmer periods. For discharge the association was less clear: Sites with (more) positive trends in discharge did not appear to have (more) positive trends in break-up.

For break-up dates the relationship with air temperature and discharge was opposite. Positive trends in air temperature corresponded with negative trends in break-up, i.e. break-up occurred earlier in warmer periods. Positive trends in discharge corresponded with negative trends in break-up, i.e. break-up occurred earlier in periods with high discharges.

It must however be noted that the periods are not concurrent, and as shown the correlation is very much dependent on which period is selected. Still, the relationship was rather consistent.

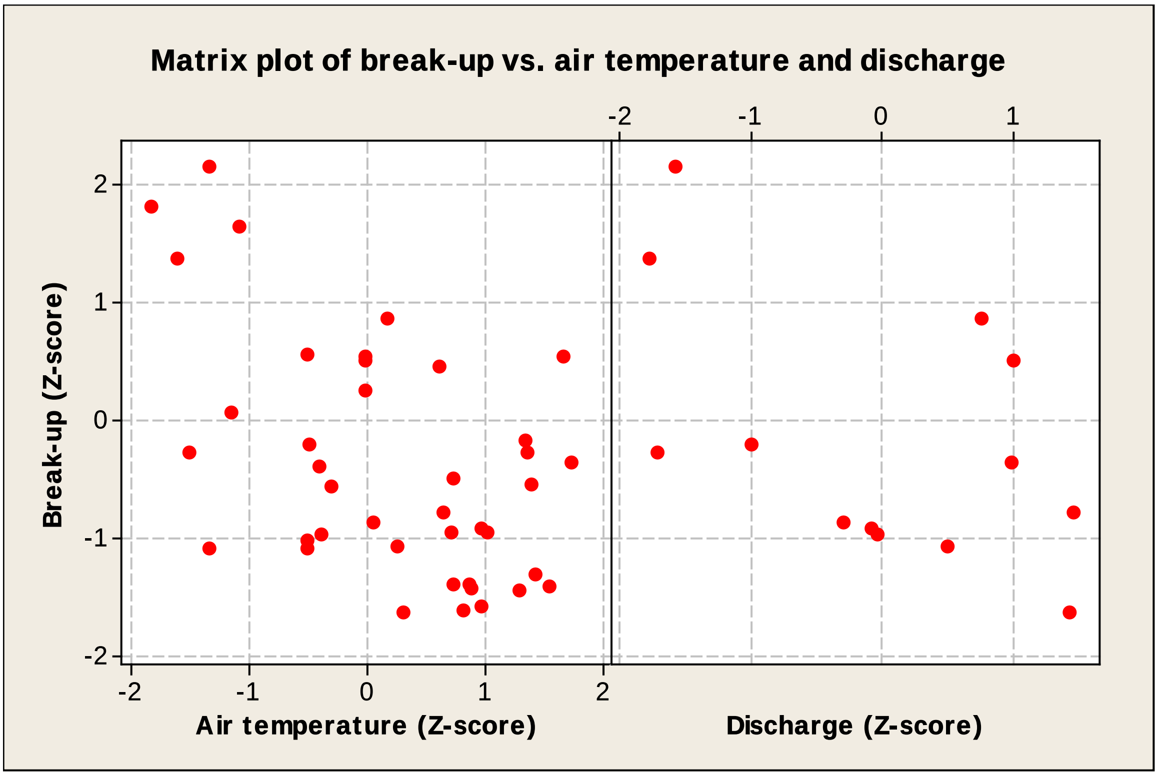


Figure 32: Scatter plots of trends (Z-scores) in break-up dates vs. trends in air temperature and discharge.

5.6.2 Seasonal air temperature during the 1953 – 84 period

Trends were also computed for autumn (September – November), winter (December – February) and spring (March – May) temperatures over the 1954 to 1983 period (Figure 33), as that period included the highest number of ice observation sites. For the sake of brevity, only the maps showing the trends have been included.

Results showed that autumn temperatures displayed a negative trend (i.e. cooling), whereas winter and spring temperatures showed mainly positive trends, indicative of warming. Autumn temperatures were generally more negative than either winter or spring temperatures were positive. The negative trend in autumn temperature was significant at two sites, whereas no significant trends were found during the other seasons.

Table 20: Trends in freeze-up dates, air temperature and discharge (rivers) in the most strongly correlated month. Note: Air temperature and discharge do not necessarily represent the same month.

		Station number	Station name	Met.no station	Period of trends	Trends (Z-score) Freeze-up	Air temperature	Month	Discharge	Month
Lake sites	Regulated	2.375.1	Aursjø	Fokstugu (16610)	1982 – 2011	1.50	−0.57	Oct		
		12.127	Bergsjø	Dagali (29720)	1973 – 2002	0.75	−0.18	Oct		
		2.162	Bygdin	Skåbu (13670)	1980 – 2009	1.26	0.65	Dec		
		2.167	Vinsteren	Fokstugu (16610)	1982 – 2011	0.00	0.32	Nov		
		2.15	Breiddalsvatn	Fokstugu (16610)	1982 – 2011	0.64	0.32	Nov		
		2.79	Tessevatn	Fokstugu (16610)	1982 – 2011	0.95	0.32	Nov		
		15.9	Tunhovdfjord	Dagali (29720)	1965 – 1994	1.86	1.12	Nov		
		2.111	Aursunden	Røros (10380)	1982 – 2011	1.38	0.87	Nov		
		12.87	Øyangen	Åbjørsbråten (23160)	1955 – 1984	−1.06	−0.43	Nov		
		2.82	Osensjøen	Rena (7010)	1982 – 2011	−0.06	0.00	Dec		
		12.89	Volbufjord	Åbjørsbråten (23160)	1946 – 1975	−1.09	−1.05	Nov		
		2.132	Lomnessjø	Rena (7010)	1943 – 1972	1.46	0.11	Oct		
		2.14	Storsjø	Rena (7010)	1982 – 2011	−0.51	0.57	Jan		
		23.2	Færåsen	Byglandsfjord (39690)	1970 – 1999	−0.54	0.57	Nov		
		77.2	Veitastrondsvatn	Fjærland (55820)	1962 – 1991	1.82	2.03	Dec		
		16.32	Hjartsjø	Gvarv (32060)	1965 – 1994	2.29	1.07	Nov		
		12.98	Krøderen	Nesbyen (24890)	1935 – 1964	0.04	−0.36	Nov		
		2.825.39	Mjøsa (Kise-Kapp)	Oslo (18700)	1984 – 2013	−0.13	0.14	Jan		
		72.7	Vassbygdvatn	Lærdal (54110)	1958 – 1987	0.18	0.59	Dec		
		62.5	Bulken (Vangsvatnet)	Voss (51530)	1961 – 1990	0.55	1.50	Dec		
	Unregulated	2.131	Atnsjø	Røros (10380)	1969 – 1998	−0.45	0.46	Nov		
		311.4	Femundsenden	Røros (10380)	1951 – 1980	−1.68	−1.86	Nov		
		311.7	Engeren	Rena (7010)	1954 – 1983	−0.71	−0.64	Dec		
		80.1	Rørvikvatn	Takle (52860)	1968 – 1997	2.00	1.39	Nov		
		307.5	Murusjø	Nordli (73450)	1972 – 2001	1.79	0.89	Nov		
		24.13.13	Lygne (sørenden)	Byglandsfjord (39690)	1980 – 2009	0.23	0.39	Dec		
		83.2	Hestadfjorden	Vangsnes (53100)	1965 – 1994	−0.65	1.22	Dec		

		314.3	Rømsjø	Rygge (17150)	1967 – 1996	0.91	0.11	Dec		
		82.1	Nautsundvatn	Vangsnes (53100)	1954 – 1983	−1.13	−0.70	Dec		
		167.3	Kobbvatn	Bodø (82290)	1948 – 1977	−0.71	−1.00	Nov		
River sites	Regulated	2.117	Stai	Rena (7010)	1969 – 1998	0.46	−0.18	Oct	−1.00	Nov
		2.2	Nor	Flisa (6020)	1954 – 1983	0.70	−0.29	Nov	0.68	Dec
		122.2	Haga Bru	Selbu (68290)	1966 – 1995	0.90	0.55	Dec	−0.86	Nov
		22.4	Kjølemo	Mandal (41110)	1935 – 1964	1.18	−0.32	Dec	0.43	Dec
		15.18	Bommestad bru[1]	Færder (27500)	1922 – 1951	−0.87	−0.88	Nov		Dec
	Unregulated	12.70	Etna	Åbjørsbråten (23160)	1967 – 1996	0.88	0.36	Nov	0.36	Nov
		311.6	Nybergsund	Rena (7010)	1944 – 1973	−0.27	−1.91	Nov	−0.47	Dec
		22.5	Austerhus	Byglandsfjord (39690)	1932 – 1961	−0.23	−0.11	Dec	0.43	Dec
		15.20	Jondalselv	Kongsberg (28380)	1965 – 1994	1.29	1.57	Nov	−0.84	Dec
		212.2	Stengelsen	Alta (93140)	1939 – 1968	1.10	0.71	Nov	2.35	Nov
		234.1	Polmak	Karasjok (97251)	1968 – 1997	1.05	0.84	Oct	−0.54	Nov

[1]Discharge data was not availbale for the 1922 – 51 period.

Table 21: Trends in break-up dates, air temperature and discharge (rivers) in the most strongly correlated month. Note: Air temperature and discharge do not necessarily represent the same month.

						Trends (Z-score)				
		Station number	Station name	Met.no station	Period of trends	Break-up	Air temperature	Month	Discharge	Month
Lake sites	Regulated	2.375.1	Aursjø	Fokstugu (16610)	1982 – 2011	0.55	−0.50	May		
		12.127	Bergsjø	Dagali (29720)	1973 – 2002	−0.95	0.73	May		
		2.162	Bygdin	Skåbu (13670)	1980 – 2009	0.06	−1.13	May		
		2.167	Vinsteren	Fokstugu (16610)	1982 – 2011	−1.09	−0.50	May		
		2.15	Breiddalsvatn	Fokstugu (16610)	1982 – 2011	−1.39	0.75	Jun		
		15.9	Tunhovdfjord	Dagali (29720)	1965 – 1994	−0.28	1.38	Apl		
		2.111	Aursunden	Røros (10380)	1982 – 2011	−1.02	−0.50	May		
		12.87	Øyangen	Åbjørsbråten (23160)	1955 – 1984	−0.50	0.75	Apr		
		139.5	Namsvatn	Nordli (73450)	1939 – 1968	−1.61	0.84	May		

	Unregulated	12.89	Volbufjord	Åbjørsbråten (23160)	1946 – 1975	1.81	−1.82	Apr		
		23.2	Færåsen	Byglandsfjord (39690)	1970 – 1999	−0.96	1.04	Feb		
		77.2	Veitastrondsvatn	Fjærland (55820)	1962 – 1991	−1.58	0.98	Apr		
		16.32	Hjartsjø	Gvarv (32060)	1965 – 1994	−1.43	0.90	Mar		
		12.98	Krøderen	Nesbyen (24890)	1935 – 1964	0.24	0.00	Apr		
		2.825.39	Mjøsa (Kise-Kapp)	Oslo (18700)	1984 – 2013	−0.56	−0.29	Feb		
		72.7	Vassbygdvatn	Lærdal (54110)	1958 – 1987	−0.39	−0.39	Feb		
		62.5	Bulken (Vangsvatnet)	Voss (51530)	1961 – 1990	−0.55	1.41	Mar		
		2.131	Atnsjø	Røros (10380)	1969 – 1998	−1.09	−1.32	May		
		311.4	Femundsenden	Røros (10380)	1951 – 1980	0.45	0.63	May		
		311.7	Engeren	Rena (7010)	1954 – 1983	−1.40	0.89	Apr		
		80.1	Rørvikvatn	Takle (52860)	1968 – 1997	−0.18	1.36	Apr		
		24.13.13	Lygne (sørenden)	Byglandsfjord (39690)	1980 – 2009	−1.32	1.45	Feb		
		83.2	Hestadfjorden	Vangsnes (53100)	1965 – 1994	−1.41	1.57	Mar		
		314.3	Rømsjø	Rygge (17150)	1967 – 1996	−1.45	1.30	Apr		
		82.1	Nautsundvatn	Vangsnes (53100)	1954 – 1983	0.54	0.00	Mar		
		167.3	Kobbvatn	Bodø (82290)	1948 – 1977	0.54	1.68	May		
River sites	Regulated	26.5	Dorgefoss	Tonstad (42810)	1948 – 1977	2.14	−1.32	Apr	−1.57	Apr
		73.1	Lo Bru	Lærdal (54110)	1948 – 1977	−0.28	−1.50	Apr	−1.71	Apr
		2.2	Nor	Flisa (6020)	1954 – 1983	−0.79	0.66	Apr	1.46	Apr
		122.2	Haga Bru	Selbu (68290)	1966 – 1995	−0.92	0.98	Mar	−0.09	Mar
		103.4	Horgheim	Sunndal (63500)	1948 – 1977	0.51	0.00	Mar	1.00	Mar
		22.4	Kjølemo	Mandal (41110)	1935 – 1964	−0.21	−0.48	Mar	−1.00	Mar
		246.1	Bjørnvatn	Karasjok (97251)	1938 – 1967	−1.64	0.32	May	1.43	May
	Unregulated	15.18	Bommestad bru[1]	Færder (27500)	1929 – 1958	1.64	−1.07	Mar		
		311.6	Nybergsund	Rena (7010)	1944 – 1973	1.36	−1.60	Apr	−1.78	Apr
		22.5	Austerhus	Byglandsfjord (39690)	1932 – 1961	0.85	0.18	Mar	0.75	Feb
		15.20	Jondalselv	Kongsberg (28380)	1965 – 1994	−0.37	1.75	Apr	0.98	Mar
		196.35	Malangsfoss	Dividalen (89950)	1937 – 1966	−0.98	−0.38	May	−0.04	May
		212.2	Stengelsen	Alta (93140)	1940 – 1969	−0.87	0.07	Apr	−0.30	May
		234.1	Polmak	Karasjok (97251)	1968 – 1997	−1.07	0.27	May	0.50	May

[1]Discharge data was not available for the 1929 – 58 period.

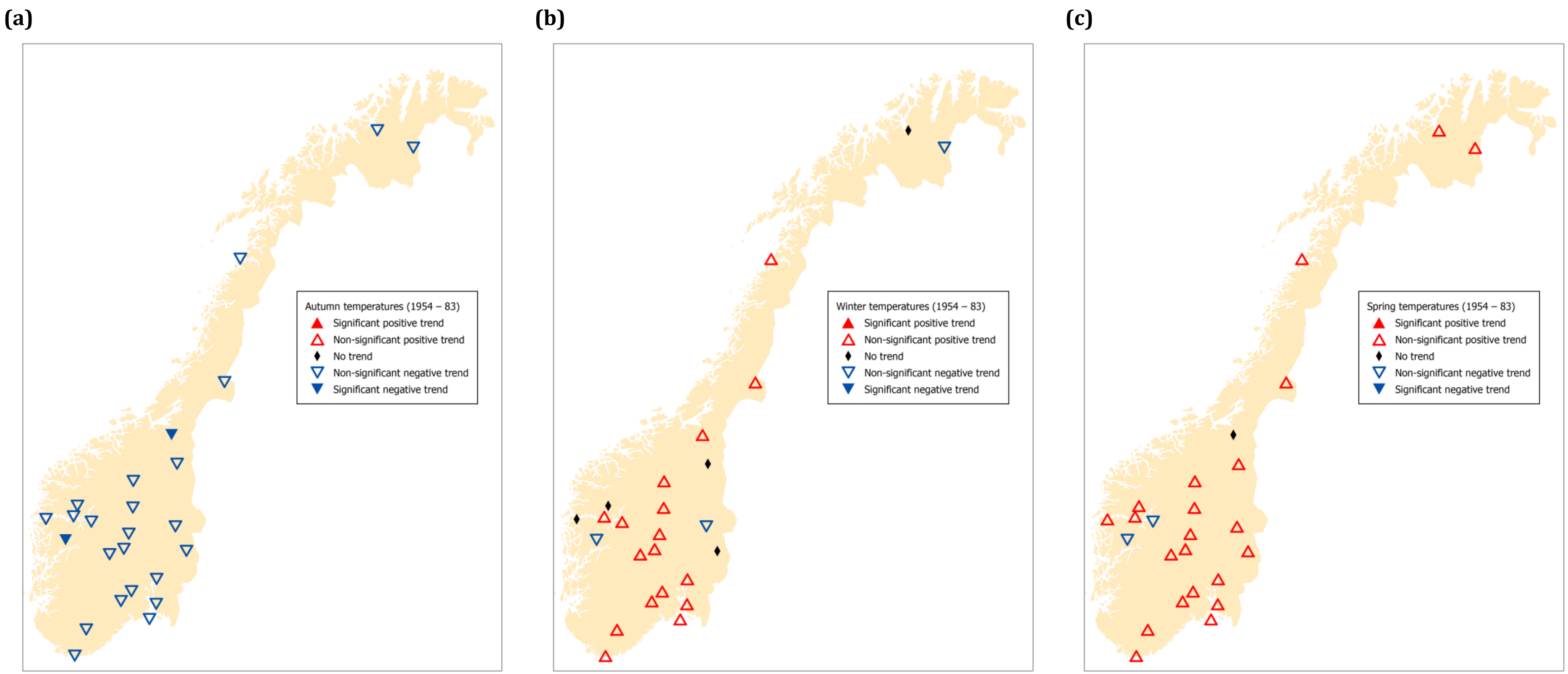


Figure 33: Trends in (a) autumn temperatures, (b) winter temperatures and (c) spring temperatures across Norway for period 1954 – 83. Triangles pointing up indicate rising temperatures, while those pointing down indicate declining temperatures. Sites with significant trends at the 5 % ($Z > |1.96|$) level are denoted by filled triangles. The cut-off point for "No trend" is defined as $Z < |0.20|$.

5.6.3 Moving 30-year periods

The temporal evolution of trends in ice phenology and hydro-meteorological variables were examined at eight selected sites by computing the trend of moving 30-year periods. Only one site was included from Trøndelag and Western Norway due to lack of complete data for lake and river sites, respectively. The selected sites were:

- Kjølemo (22.4) and Lygne (24.13.13) in Southern Norway
- Mjøsa (2.825.39) and Etna[4] (12.70) in Eastern Norway
- Veitastrondsvatn (77.2) in Western Norway
- Haga bru (122.2) in Trøndelag
- Kobbvatn (167.3) and Polmak (234.1) in Northern Norway

The results are shown in Figure 34, Figure 35, Figure 36 and Figure 37. Computed trends are for the 30-years prior to the year displayed on the x-axis. Trends over the 1931 – 60 will be displayed as "1960" on the plots. The trends in air temperature and discharge were inverted (sign change) in plots of break-up dates for illustrative purposes. As the three are negatively correlated, it was difficult to identify possible similarities in trends from the original plots.

Results display large temporal changes in the 30-year trends. For a majority of the sites, the freeze-up and break-up trends were both significantly positive and negative at some point during the examined period. Trends in ice phenology generally appeared to follow trends in hydro-meteorological variables rather closely, though some clear exceptions from this were displayed. The fluctuations in trends appeared to be larger for ice phenology than for the hydro-meteorological variables.

[4] The break-up record for Etna (12.70) was initially excluded from the trend analysis. See Section 6.1 of the discussion for more details.

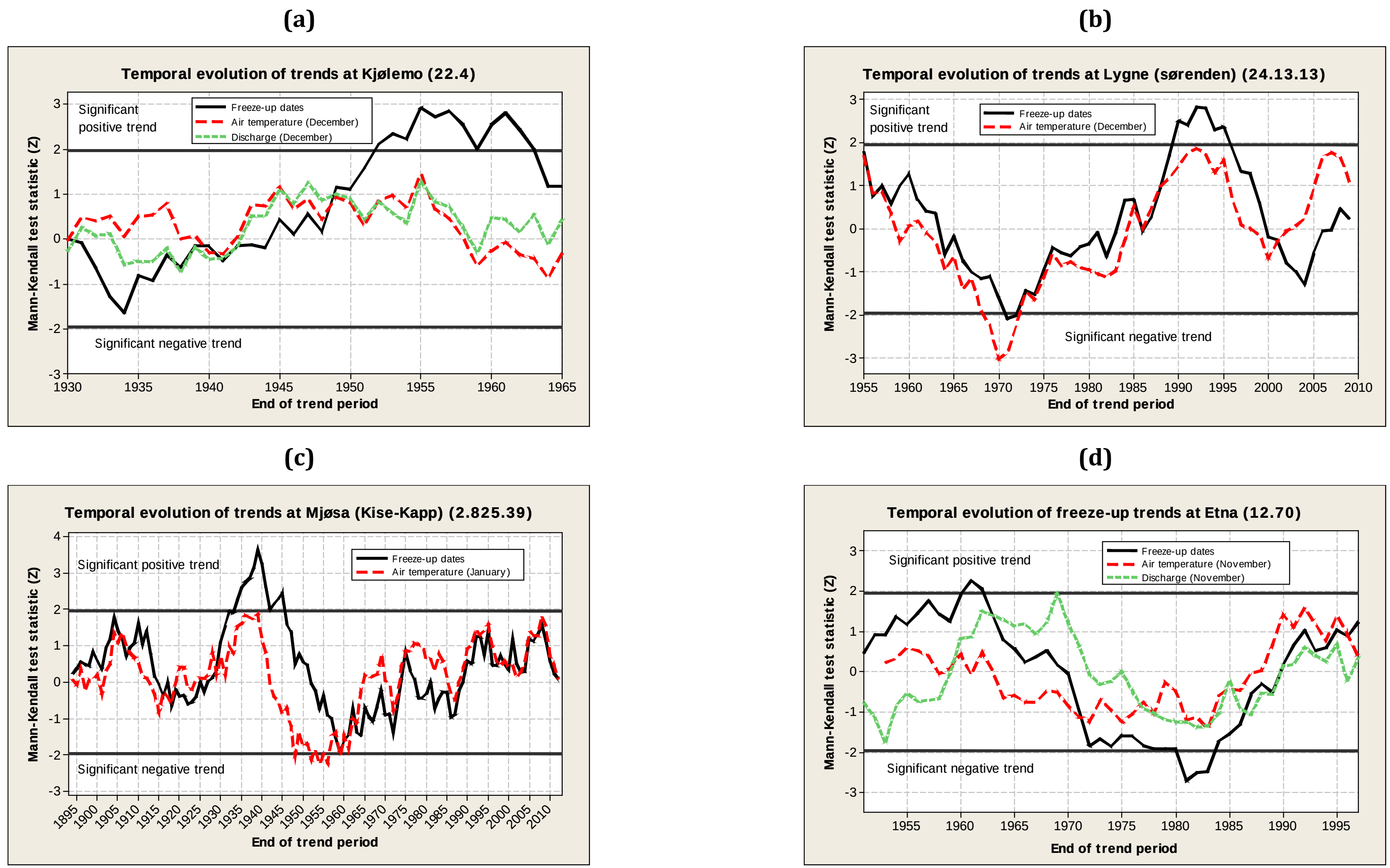
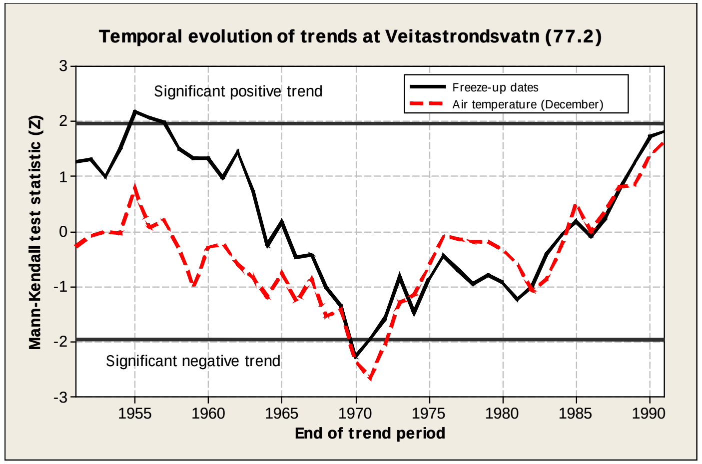
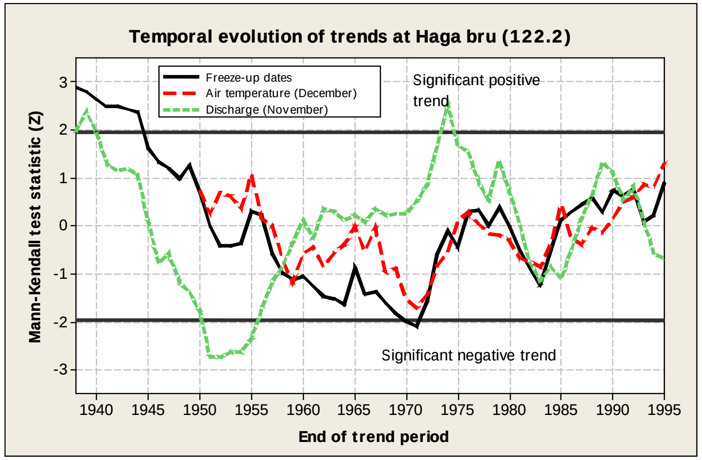


Figure 34: Temporal evolution of trends in freeze-up and air temperatures and discharge at (a) Kjølemo, (b) Lygne, (c) Mjøsa and (d) Etna.

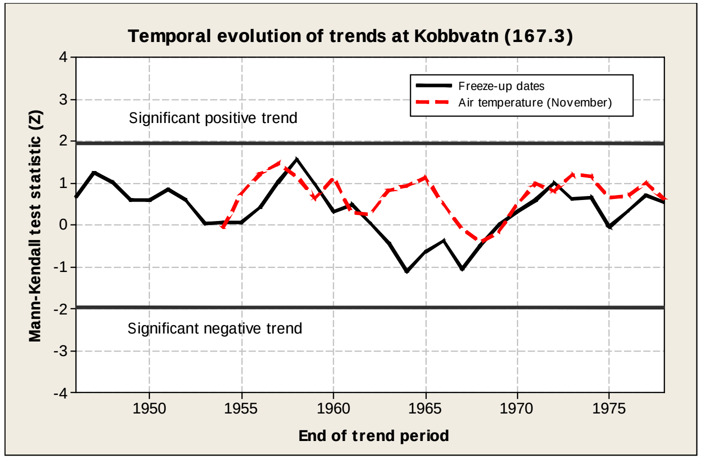
(a)



(b)



(c)



(d)

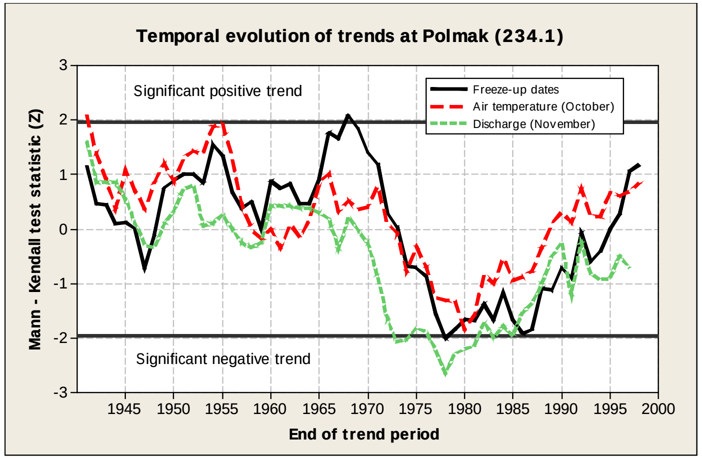
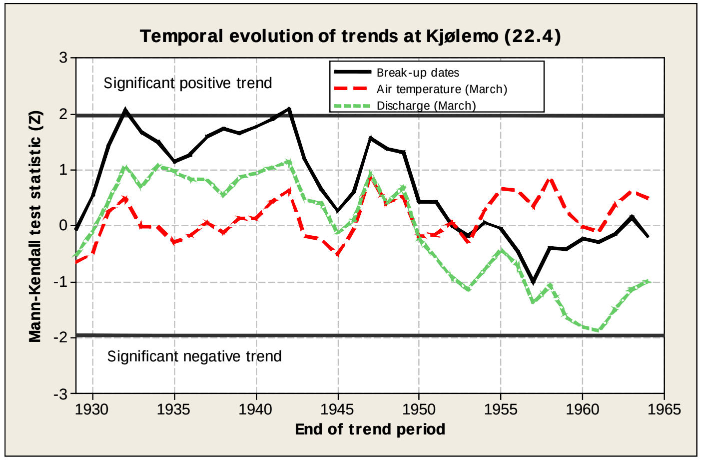
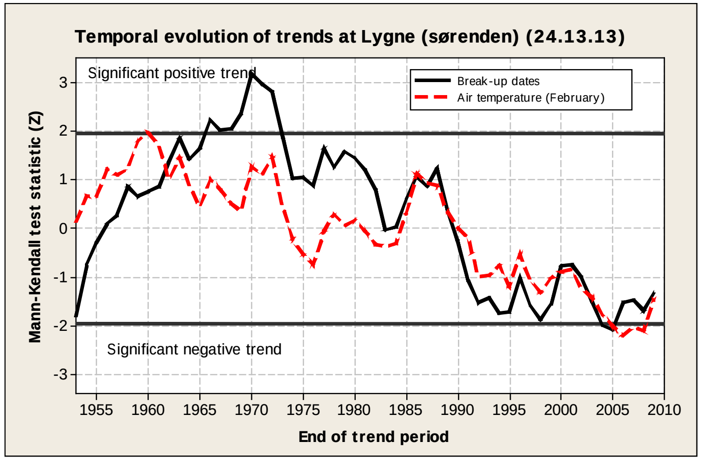


Figure 35: Temporal evolution of trends in freeze-up and air temperatures and discharge at (a) Veitastrondsvatn, (b) Haga bru, (c) Kobbvatn and (d) Polmak.

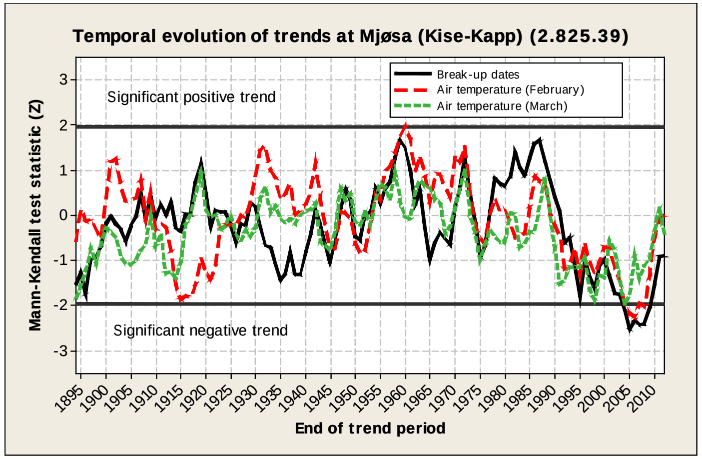
(a)



(b)



(c)



(d)

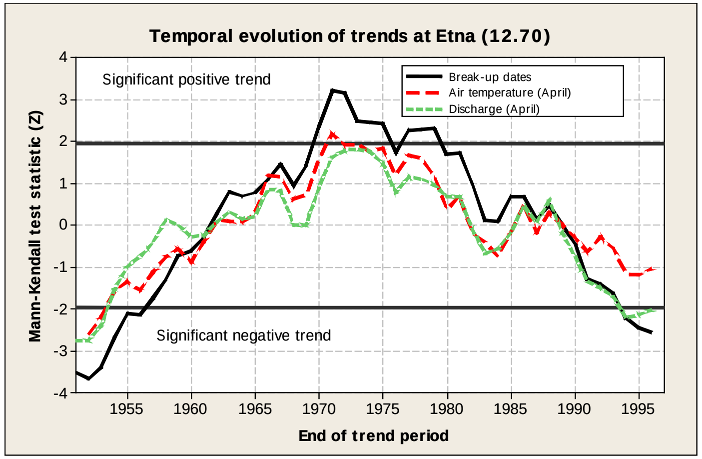
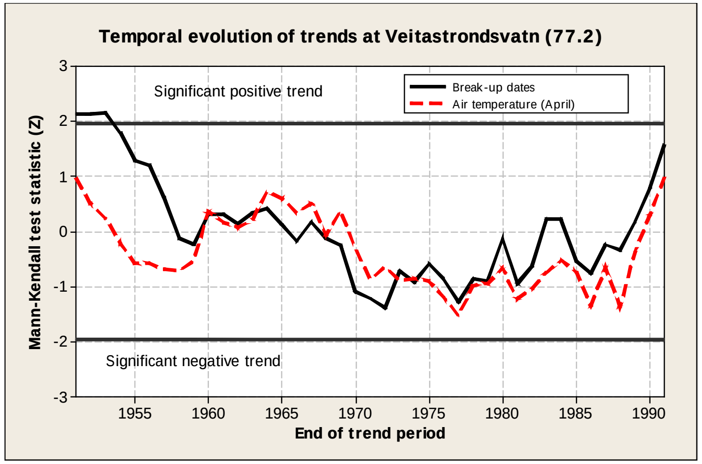
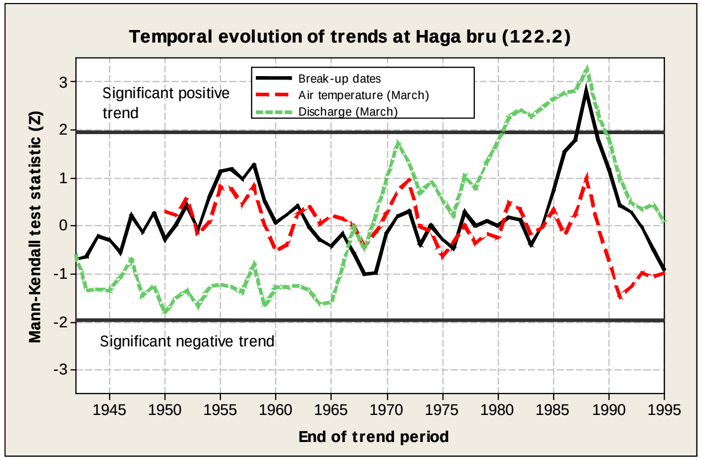


Figure 36: Temporal evolution of trends in break-up, air temperature and discharge at (a) Kjølemo, (b) Lygne, (c) Mjøsa and (d) Etna. The trends in air temperatures and discharge have been inverted for illustrative purposes.

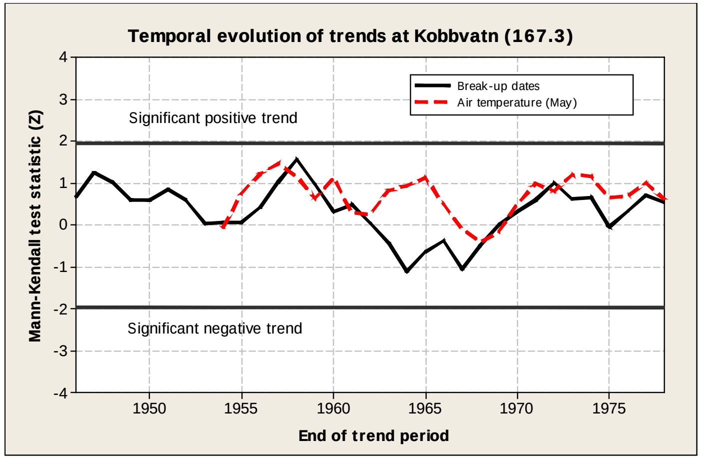
(a)



(b)



(c)



(d)

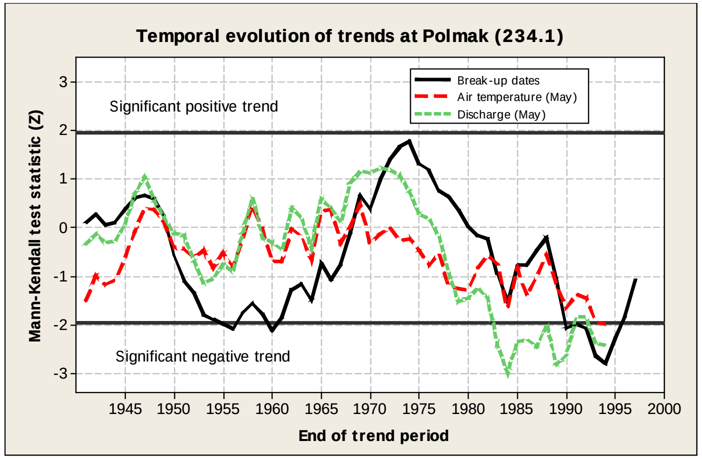


Figure 37: Temporal evolution of trends in break-up, air temperature and discharge at (a) Veitastrondsvatn, (b) Haga bru, (c) Kobbvatn and (d) Polmak. The trends in air temperatures and discharge have been inverted for illustrative purposes.

6 Discussion

6.1 Quality control and homogeneity testing

Ideally only unregulated sites should have been used for this type of analysis. However, relatively few long records can be found from unregulated locations. If the effect of the regulation can be assessed and found minor (i.e. homogenous), a meaningful trend analysis can still be performed. The results displayed only minor differences in trends of ice phenology between regulated and unregulated over concurrent. Hence, it might be an indication of that the process of homogeneity testing had the intended effect, i.e. sites with biases from regulations were excluded.

For the sake of consistency, all records classified as “suspect” were dropped from the subsequent analyses. Records classified as “doubtful” were also dropped, with three exceptions. As consequence of this, several of the longest records (Aursunden, Femunden, Krøderen etc.) were classified as “suspect” and removed from the analysis or considerably shortened.

In the case of Aursunden (2.111), all tests detected an abrupt shift in the freeze-up around the year 1935. Metadata was scarce, but available information indicated that the lake was regulated twice, with the last regulation completed in 1923/24. Hence, it seemed unlikely that the shift was caused by the regulation as that occurred more than ten years prior. Other possible explanations could have been a relocation of the observer or changes in the routines for observations. However, as long as the metadata was limited, the exact cause could not be determined.

The break-up record from Etna (12.70) was initially excluded from the trend analysis due to a detected homogeneity break. No explanation for the detected break-up could be found in the limited metadata. For the sake of curiosity, it was decided to include Etna in the analysis of temporal trends. Figure 36d show that trends in break-up, air temperature and discharge at Etna was highly correlated. It is fairly unlikely that a homogeneity break occurred at the same time in both air temperature and discharge records. Thus, it could be argued that the dectected break may not be real (i.e. a rejection of H_0 when H_0 is true – Type I error).

The examples of Aursunden and Etna further underline the need for extensive explanatory metadata in the homogeneity testing process. The fact that statistical tests detected homogeneity breaks, do not necessarily mean that there is an *artificial* break in the record. As shown by Toreti et al. (2011) and Martínez et al. (2010; 2011), absolute tests are sensitive to transient natural phenomena as they do not compare with neighboring stations. However, events that occur simultaneously at several sites will not necessarily be detected by relative homogeneity tests either (such as simultanous changes in routines at observation sites etc.).

It is possible that some of the records classified as “suspect” or “doubtful” were homogenous, and that the tests incorrectly detected breaks where there were none (Type I error). Contrary, it is also possible that some of the records that were classified as “Useful” contained inhomogeneities (Type II error). A thorough examination of all available metadata could probably shed more light on this. Unfortunately, this was not feasible due to relative size of the data set, the time constraints and the lack of extensive metadata beyond the basic information on which sites were regulated and unregulated.

6.2 Trends in ice phenology and hydro-meteorological variables

Trends in ice phenology varied extensively in both time and space. For long-term records (non-concurrent periods of varying length), both positive and negative trends in ice phenology were found. However, the general signal pointed towards a shorter period with ice cover. That is, either the freeze-up dates became later or break-up became earlier over the long-term period. Trends in ice cover duration were significant and negative at 20 % of the sites. For the fixed 30-year periods the picture varied somewhat.

The first period covering the years between *1913 and 1942* displayed no clear signals in trends of ice phenology. A total of 13 sites displayed trends towards either later freeze-up or earlier break-up, whereas the opposite was true for 11 sites. Plots of temporal evolution of trends in ice phenology and hydro-meteorological variables were mostly in agreement, and showed neutral trends during this period.

The *1954 – 83* period displayed clear signals in trends of ice phenology. A total of 16 sites showed trends towards either later freeze-up or earlier break-up, whereas the opposite was true for 32 sites. The trends were largely mirrored in the trends of seasonal air temperatures for the period, though site-to-site variation was considerable. The latter is indicative of two things: (i) seasonal air temperatures are not necessarily the best method to explain trends ice phenology, but they it was chosen to display comparable values; (ii) air temperature is not the only variable that affects ice formation and break-up. A discussion of other variables and why they were not included in the analysis is given in Section 6.4.

The *1982 – 2011* period displayed trends towards either later freeze-up or earlier break-up at 12 sites, whereas the opposite was true for 3 sites. Hence, a clear signal pointing towards a shortening of the ice covered period. Trends in air temperatures (Table 20; Table 21) of the most strongly correlated months were not as clear, and trends varied from positive to negative at the sites. Trend evolution plots of Mjøsa indicated that the direction of trends (i.e. the derivative) of both freeze-up and air temerature and break-up and air temperature were postive and negative, respectively. Whether this trend will continue in the future is uncertain. However, if the latest estimates by the Intergovernmental Panel on Climate Change (IPCC) are correct, the trend is likely to continue (Hansen et al., 2012)

During the *1922 – 1994* period 10 sites displayed trends towards either later freeze-up or earlier break-up, whereas the opposite was true for 5 sites. Hence, a clear sign pointing towards a shortening of the ice covered period could be found. The trend displayed a strong spatial coherence for break-up dates, wheares patterns in freeze-up and ice cover duration were less clear.

The fact that Northern Norway is represented by so few sites undoubtedly affects the inference of the results. As can see from trends in the southern regions of Norway (where the most sites are located) during 1954 – 83 period, there wass considerable variation in trends even at sites located near each other. There is really no reason to think that similar local varation is present in Norway. Hence, any apparently clear patterns may not have been as clear if more sites had been included (if the data existed) for Northern Norway.

Periods and the use of monthly data

Previous studies on trends in phenological variables (Duguay, 2006; Korhonen, 2006) have shown that the detected trends are very much dependent on which period is examined. By choosing different periods in the records, different trends can be found. This was also shown to be correct for Norwegian ice records (as well as air temperature and discharge). As demonstrated by maps of fixed 30-periods and plots displaying the temporal evolution of trends, the temporal variation was considerable. Longer periods (40-50-60-70-years) would have been less fluctuating, but at the same time would have masked shorter-term trends, as well as reduced the number of sites available for analysis.

At several of the selected sites (Figure 34; Figure 35; Figure 36; Figure 37) the 30-year trends were both significantly positive and negative at times during the examined period. These large temporal variations seemed to be present in most records, and were not limited to certain regions, sites or geographical localities. However, some sites displayed less variation.

In some periods the correlation changed abruptly to the worse/lower. This was usually indicative of that another month was better correlated during that period, i.e. it was either a colder or warmer period. In the case of break-up dates of Mjøsa, colder periods lead to higher correlation with March temperatures, while warmer periods lead to higher correlation with January temperatures. Overall, the break-up was somewhat better correlated with February temperatures.

With some variations, the trends in ice phenology appeared to follow the trends in air temperature fairly closely. That was also the case with Mjøsa, though some periods deviated markedly from this. The trend in freeze-up dates of Mjøsa turned extremely positive in the 1930s (Figure 34c), much more so than the January temperatures. The trend in freeze-up dates appeared to lag some 5 – 10 years behind the corresponding trend in air temperatures. A possible explanation for the given period could be that January was not the best correlated month at the time, but that did not appear to be the case, as February and March displayed even lower correlation.

Monthly air temperature and discharge were used as explanatory variables for changes in freeze-up and break-up in this thesis. However, months are in reality an artificial "construction" made by humans, which has moderate to minor (real) relation to the actual weather conditions (other than the underlying large scale pattern). The periods of freeze-up and break-up may occur during colder periods in the transition between months, and hence not be "picket up" in monthly averages if the rest of the month are warmer. Seen in retrospect, it could have be more beneficial to use 0°C isotherm dates instead, as was done by Duguay et al. (2006). However, daily data is not available from most stations before 1957. In addition, the daily data have not been tested for homogeneity breaks. Hence, that would have introduced a new set of challenges.

A similar challenge may lie in the use of monthly discharge data. Other studies have used daily discharge data to correlate against break-up dates. Gebre and Alfredsen (2011) suggested that daily discharge was more strongly correlated with break-up than monthly averages, and that this was due to the (often) dynamic nature of river ice break-ups (ice runs). Though that was true for a couple of sites used in this study, there was little meaningful difference between the correlation of break-up with monthly and daily discharge for the large majority of sites. In most instances the break-up dates actually correlated better with monthly discharge than it did with daily values. For simplicity, only monthly average discharged were used in the analysis.

6.3 Comparison with other studies

Most Norwegian ice records are relatively short, with only a handful of the records exceeding 75 years (Table 12). Hence, making relevant comparisons with other (international) studies may be difficult, as these typically have used much longer records, often in excess of 100 years. The only Norwegian record of such length is the Mjøsa record, commencing in 1865. Mjøsa displayed positive trends in freeze-up and negative trends in break-up over the 1865 – 2013 period, though only the former was significant at the 5 % level (Table 13; Table 14). Furthermore, the trend in ice cover duration was negative and significant (Table 15). The rate of change in freeze-up dates was 1.2 days/decade, whereas the change in ice cover duration was
–1.3 days/decade.

Magnuson et al. (2000) and Korhonen (2006) found trends in both freeze- and break-up of Finnish lakes during the 1846 – 1995 period, though only the break-up trends were significant at the 5 % level. Hence, the detected trends were completely opposite of those found in the Mjøsa record. However, it should be noted that the Finnish lakes included in the study were relatively shallow compared to Mjøsa (<100 m vs. 453 m deep). Some deeper lakes were also included by Magnuson et al. (2000): Both Lake Baikal (~1 650 m deep) in Russia and Great Traverse Bay (~180 m deep) in the US displayed significant positive trends in freeze-up dates. The rates of change in freeze-up for these sites were approximately 1.1 days/decade, i.e. very similar to that of Mjøsa. For all sites, the total shortening of the ice covered period was found by Magnuson et al. (2000) to be in the order of –1.2 days/decade. This was is in good agreement with the findings from Mjøsa, even though both methods and periods for trend analyses differed.

Shallow[5] Norwegian lakes (Hjartsjø, Lomnessjø, Vinsteren) typically display the strongest correlation with October and November temperatures. According to Korhonen (2006) the same is true for most Finnish lakes. Deep Norwegian lakes (Lygne, Mjøsa, Storsjø) show the strongest

[5] The pattern is somewhat complicated by the fact the lakes are located at very different elevations. See Appendix A for information on lake depth.

correlation with December and January temperatures. Hence, the lack of trends in freeze-up of Finnish lakes might be an indication of larger increases in December and January temperatures than in October and November temperatures. I.e. an ice cover is usually present in December and January, increased temperatures will not necessarily affect the ice cover (unless temperature increases a lot). For lakes where ice cover has not formed at that point, any temperaure increases will cause a delay of freeze-up.

The findings of Hodgkins et al. (2002) indicated that break-up had become consistently earlier at studied sites with the longest records (> 100 year of data). For sites with less than 100 years of data few significant trends were found by Hodgkins et al. (2002). This is in accordance with the findings in this thesis. A majority (65 %) of Norwegian ice records did display long-term negative trends in break-up, but few were actually significant. The longest record (Mjøsa) did however not display a significant trend in break-up dates.

As discussed in the review section, the results of Gebre and Alfredsen (2011) are not directly comparable due to different methodologies. The effect of different methodologies becomes evident when comparing the computed trends of Mjøsa over a common period. The Mjøsa record has a high number of no-ice years, and thus the results will depend greatly on how these are handled. Gebre and Alfredsen (2011) found freeze-up and break-up trends for Mjøsa of $Z = 2.07$ and $Z = 0.34$, respectively. These z-scores approximately equal to those found in this thesis when computing the trend without no-ice years. In contrast, the trends found, when applying the method suggested by Assel and Robertson (1995), were $Z = 3.30$ and $Z = -1.49$, a substantial difference. Hence, ignoring no-ice years in the analysis will considerably bias the results towards earlier freeze-up and later break-up.

On another note: It is common that studies on trends in ice phenology offer no discussion on either data quality, missing data or homogeneity of the ice records. Experience show that Norwegian ice records are relatively imperfect, i.e. there are missing observations, erroneous values and even homogeneity breaks due to various causes. There is no reason to believe that such problems are not prevalent in other parts of the world too. Hence, it could be useful view (seemingly) “perfect” ice records with some degree of skepticism. It is likely that some kind of quality control have been performed on foreign ice records, and missing values have probably been filled-in. However, as long as the methodology is unknown, it is difficult to evaluate the process.

Furthermore, several studies of trends in ice phenology variables have used parametric methods (mainly linear regression) without problematizing the issue of normality (Magnuson et al., 2000; Korhonen, 2006; Jensen et al, 2007). As was shown in section 4.2.1, ice records are not necessarily normally distributed. If parametric methods have been applied to non-normal data, it will affect the inference of the results. Hence, the results in this and the above-mentioned are not necessarily comparable.

6.4 Other possible explanatory variables

As none of the sites displayed perfect correlation with either air temperature, discharge or both, other explanatory variables (indicative of underlying processes) must be present. As shown in section 2.1.3, the heat loss from an open water surface is highly dependent on wind speed (Figure 3), while ice growth was greatly affected by snow cover (Equation 4).

Wind

Wind is an important factor in the formation of ice cover on lakes and rivers. Prior to ice formation, higher wind speeds will contribute to more effective mixing of the water in lakes and thus increased heat loss and more rapid cooling. In large lakes, calm conditions must persist for several days during the ice formation for the ice cover to grow to the necessary thichness, making it strong enough to withstand shear stress caused by the wind. The heat loss due to wind is also important in rivers, though the mixing of water due to wind is probably negligible.

Wind shear stress can be play a significant role during the break-up of lake ice. Hence, stronger winds could lead to earlier break-up of the ice cover. For Norwegian rivers the wind is generally of little importance for the break-up, as they are relatively narrow. Given the above, increased winds can lead to both earlier and later formation of ice, as well as earlier og later break-up (decreased wind) of ice.

Wind observations are available for most Norwegian weather stations post-1957, but several challenges make it difficult to use the wind data for trend analysis. Historically (pre-1980s to 2000s) wind speed was not measured, but rather based on qualitative assessments made by the observer. Wind conditions were classified using a modified version of the Beaufort scale, and scale values were later converted to wind speed based on an empirical relationship. Beginning in the 1980s cup anemometers were gradually introduced at Norwegian weather stations (eKlima, 2013; met.no, 2013), though some airport and coastal stations had anemometers before this.

Given the observational history, long-term Norwegian wind records are likely to contain several homogeneity breaks. The most obvious source of inhomogeneity is the transition from subjective observations to objective measurements. Other possible causes for homogeneity breaks include changes in observers and observation practices in the pre-instrumental era, but also more recent changes in the instrumentation (anemometers). Any modifications to the surroundings are also likely to cause inhomogeneities in the wind data (Wern and Bärring, 2009).

The subject of homogeneity in historical wind data has been relatively poorly covered in Norwegian literature. Førland et al. (2007) suggests that few long-term homogenous wind records exist, but little factual information is given in the publication. Dyrdal et al. (2011) refers to an internal report from met.no where several wind records were tested and found homogenous, but these were apparently only instrumental records. For published studies of long-term trends in Norwegian wind conditions geostrophic winds (or re-analysis) have almost exclusively been used (Harstveit, 2005; Førland et al., 2007; Benestad, 2010). An evaluation of Swedish wind data by Wern and Bärring (2009) found no homogenous long-term wind records, mainly due to the problems described above. The result of the Swedish evaluation is probably fairly representative for Norway as well based on/given similarities in observation practices etc.

In addition to the homogeneity considerations, it should be stressed that wind speed is a highly local phenomenon. The large scale patterns may be reflected in the sites, but somewhat similar to precipitation, the wind speed is affected by the local topography. As the meteorological stations were not located at the ice observations sites, the correlations were generally thought to be low. This assumption is backed by the findings of Holmsen (1901) who unsuccessfully attempted to quantitative assess the relationship between monthly wind speed and freeze-up/ break-up dates.

Given the large uncertainty regarding the homogeneity of the data and the doubt whether it was really a (practically) meaningful explanatory variable, wind speed was dropped from the analysis.

Precipitation

Norwegian precipitation data was shown by Hanssen-Bauer and Førland (1994 to suffer from serious problems with inhomogeneities. The problems encountered in precipitation records were similar to those problems affecting temperature, i.e. changes in observers, routines and the introduction of wind screens. For air temperature the problem with homogeneity breaks could be alleviated by using homogenized data (i.e. data that has been tested and found homogenous). Homogenized precipitations records had also been prepared (Hanssen-Bauer and Førland, 1994), but were unfortunately not available at eKlima. For that reason precipitation was not included as an explanatory variable in the analyses.

Precipitation is linked to freeze-up and break-up through discharge, but also through the considerable heat loss caused by falling snow melting at the water surface. The discharge is dependent on precipitation and air temperature (a snow/rain threshold). If the air temperature is below 0 °C, the precipitation will be stored as snow. In winters with large amounts of snow, the snow storage can lead to high spring floods (depending on the temperature and precipitation during the melting period). The exact timing of the melting, however, is determined by air temperatures. Hence, air temperature is the governing factor for determining the discharge in freeze-up and break-up situations.

Snow depth

The presence of a snow cover on the ice surface will significantly alter the heat exchange between the ice and the atmosphere. As shown by Equation 2 and Figure 6, ice thickness is largely determined by snow depth, snow state (i.e. light/dense, wet/dry) and air temperature. Snow depth in turn is determined by temperatures and precipitation, though the first is really the decisive factor, i.e. snow cover will not form unless the air temperature is below 0 °C. Hence, in the long run snow cover and thus ice thickness will be determined by air temperatures.

Previous studies (Jensen et al., 2007) have included snow depth as an explanatory variable. However, Norwegian snow depth data have not been tested for homogeneity breaks by met.no. For that reason snow depth data was not included in the analyses.

6.5 The future

6.5.1 Further work

This thesis has focused mainly on trends and in the mean value, as opposed to changes in the variability. Studies show that climate changes can not only manifest itself as changes in the mean value, but also changes in the variability, i.e. changes in the shape of the distribution (increased skewness and/or kurtosis) (Hansen et al., 2013). Hence, it could be interesting to specifically examine possible changes in variability of the freeze- and break-up dates. From what can be discerned from available literature, this subjected has not been covered. An analysis might improve the knowledge and understanding of the effects of climate change on the variability in ice phenology data. For such analyses the long-term homogenous records could be used.

6.5.2 Suggestions for future ice observations

As forecasted global warming is anticipated to be largest at high latitudes, continued monitoring of Norwegian ice records can provide an early indicator of predicted global and regional warming. Ice records are especially important be cause they integrate climatic conditions during the period (autumn-winter-spring) when the most warming is forecast to occur. As shown, changes and trends in ice records may be even more consistent than air temperature records themselves.

Ice observations should be resumed at sites where the original records are long and uninterrupted, with few missing values and data gaps and of generally high quality. The observation site should not adversely affected by regulations (i.e. homogenous). Moreover, complete ice cover should be a yearly occurrence at the site, at least if quantification of changes beyond (0/1) is desirable. As described in section 4.1.2, years without ice is a challenge in ice phenology trend analyses. The problem can be handled using various approaches, but there is some uncertainty as to whether (or not) these offer a satisfactory solution. Hence, the best approach would be to avoid sites were ice-free winters are a frequent occurrence – if the data is to be used for trend analysis (with a quantification of the change in the number of ice covered days as a “product”).

The practical side of the problem, i.e. the actual collection new ice observations could be tackled in several ways. High resolution satellite data (Landsat images) could probably be utilized, as suggested by Gebre and Alfredsen (2011). Another solution could be to equip relevant hydrometric stations with web cameras.

7 Conclusion

Norwegian ice records from a high number of sites, covering the time period from 1865 to 2013 were quality controlled and tested for homogeneity. The vast majority of sites were classified as homogenous. Trend analyses were performed on the homogenous records, and any trends were attempted explained with similar trends in air temperature and discharge. The results of trend analyses displayed large variations in both in space and time.

- Trends towards both later and earlier *freeze-up* dates were found at various locations across Norway. Most trends were not significant at the 5 % and their spatial coherence was generally weak for most examined periods. For long-term records, approximately the same number of sites displayed a trend towards later freeze-up than did the opposite.

- Trends toward earlier and later *break-up* dates were found at various locations across Norway. Most trends were not significant at the 5 % and their spatial coherence was generally weak for most examined periods. However, for long-term records, a higher number of sites displayed a trend towards earlier break-up than did the opposite.

- Trends *in ice duration* towards shorter and a longer duration was found at various locations across Norway. Most of these trends were not significant at the 5 % and their spatial coherence was generally weak for most periods examined. However, for long-term records, a higher number of sites displayed a trend towards shorter duration of ice cover than did the opposite.

The detected changes in ice phenology corresponded well with changes in temperatures and discharge at most sites.

The longest record (Mjøsa), covering the 1865 – 2013 displayed significant positive trends in freeze-up and significant negative trends ice cover duration at the 5 % level. The detected rates of change were 1.2 and –1.3 days/decade, respectively. This is similar to the findings of comparable studies from Eurasia and North America.

8 References

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9 List of Appendices

Appendix A – Summary of metadata

		Station number	Station name	When?[a]	Catch-ment area (km²)[b]	Surface area (km²)[c]	Max. depth (m)[d]	Runoff (l/s·km²)[e]	Discharge (m³/s)[f]	Drainage basin[g]	Region[h]
Lake sites	Regulated	2.375.1	Aursjø	1919/65	109	7,4	24	13		Glommavassdaget	EN
		12.127	Bergsjø	1949	28	1,7		30		Drammensvassdraget	EN
		2.162	Bygdin	1936	306	40,0	200	43		Glommavassdaget	EN
		2.167	Vinsteren	1942/50	463	28,2	37	37		Glommavassdaget	EN
		2.15	Breiddalsvatn	1948/2008	128	6,6	45	44		Glommavassdaget	EN
		2.79	Tessevatn	1941/63	225	12,8	68	14/29		Glommavassdaget	EN
		15.9	Tunhovdfjord	1920	1 858	25,6		20		Numedalslågen	EN
		2.111	Aursunden	1896/1924	849	46,1	60	23		Glommavassdaget	EN
		12.87	Øyangen	1918/81	246	6,6	73	31		Drammensvassdraget	EN
		139.5	Namsvatn	1949	710	39,4	84	45		Namsenvassdraget	TR
		2.82	Osensjøen	1928	1 176	43,6	117	18		Glommavassdaget	EN
		12.89	Volbufjord	1918/81	675	3,9	67	21		Drammensvassdraget	EN
		2.132	Lomnessjø	1971	1 165	3,7	26	14/42		Glommavassdaget	EN
		2.14	Storsjø	1947/71	2 293	47,9	309	14/42		Glommavassdaget	EN
		23.2	Færåsen	1920	34	1,2		49		Audnavassdraget	SN
		77.2	Veitastrondsvatn	1983	386	17,5	151	74		Årøyvassdraget	WN
		16.32	Hjartsjø	1959	214	1,1	44	27		Skiensvassdraget	EN
		12.98	Krøderen	1956 – 70	5 111	43,9	130	23		Drammensvassdraget	EN
		2.825.39	Mjøsa (Kise-Kapp)	1909/41/63	16 568	369,0	453	19		Glommavassdaget	EN
		72.7	Vassbygdvatn	1973 – 89	759	1,8	65	48		Aurlandsvassdraget	WN
		62.5	Bulken (Vangsvatnet)	1969/77	1 092	7,8	60	65		Vossovassdraget	WN
	Unregulated	2.131	Atnsjø		463	5,0	80	22		Glommavassdaget	EN
		311.4	Femundsenden		1 794	203,5	150	14		Trysilvassdraget	EN
		311.7	Engeren		395	11,6	80	19		Trysilvassdraget	EN
		80.1	Rørvikvatn		21	1,0		91		Dyrneslielvvassdraget	WN
		307.5	Murusjø		346	7,2		25		Ångermanelven	TR
		24.13.13	Lygne (sørenden)		272	7,7	193	66		Lygnavassdraget	SN
		83.2	Hestadfjorden		508	3,2	63	84		Gaularvassdraget	WN
		314.3	Rømsjø		140	13,7	100	15		Vänern - Göta älv	EN

		82.1	Nautsundvatn		219	0,7	97		Guddalsvassdraget	WN
		167.3	Kobbvatn		387	5,1	64		Kobbelvvassdraget	NN
River sites	Regulated	26.5	Dorgefoss	1972	809		61/3	50/2	Siravassdraget	SN
		73.1	Lo Bru	1974	562		27	15	Lærdalsvassdraget	WN
		2.117	Stai	1924/71	8 932		15/10	138/91	Glommavassdaget	EN
		2.2	Nor	1924	18 932		16	295	Glommavassdaget	EN
		122.2	Haga Bru	1923→	3 061		26	80	Gaulavassdraget	TR
		103.4	Horgheim	1975	1 099		33	37	Raumavassdraget	WN
		22.4	Kjølemo	1932 →	1 758		47	82	Mandalselva	SN
		246.1	Bjørnvatn	1930 →	18 110		9	165	Pasvikelva	NN
		15.18	Bommestad bru	1920 →	5 535		20	111	Numedalslågen	EN
	Unregulated	2.130	Atna Bru		464		23	11	Glommavassdaget	EN
		12.70	Etna		570		17	9	Drammensvassdraget	EN
		311.6	Nybergsund		4 425		15	68	Trysilvassdraget	EN
		22.5	Austerhus		413		44	18	Mandalselva	SN
		15.20	Jondalselv		154		22	3	Numedalslågen	EN
		196.35	Malangsfoss		3 111		26	82	Målselvvassdraget	NN
		212.2	Stengelsen		6 357		13	83	Altavassdraget	NN
		234.1	Polmak		14 163		12	170	Tanavassdraget	NN

The data in the table have for the most part been gathered from http://atlas.nve.no and http://www.glb.no/.

Notes:

(a) The year usually implies when the regulation of the water course took place. If only the year when the license was granted is known, this is marked with (L). An arrow (→) indicates that several regulations have been carried out, with the first regulation in the given year.

(b) Catchment area (km^2) is the total catchment area upstream of the gauging station. In some cases water is transferred from neighboring catchments increasing the "effective" catchment area.

(c) Surface area (km^2) is the surface area of the lake.

(d) Reg. volume is the volume of the regulated part of the lake, i.e. the difference between the lake volume at the highest regulated water level and the lowest regulated water level. Some of the lakes aware not dammed, but instead (probably) affected by upstream regulations. These are marked as "none". None of the river sites have been affected by damming at the observation site, but instead by regulations (damming and/or transfer of water either from or to the catchment from a neighboring catchment). The regulation percentage could probably have been calculated for such a site, but that was not relevant for this study. The numbers in the table are for illustrative purposes only.

(e) The runoff is the yearly runoff in $l/s \cdot km^2$ averaged over the 1961 – 90 period. The data has been gathered from atlas.nve.no and is subject (?) to a ~20 % margin of error. In the case of a forward slash line (/) the number indicates runoff before and after regulation, respectively.

(f) The discharge is the average yearly discharge in m^3/s over the 1961 – 90 period. The data has been gathered from atlas.nve.no and is subject (?) to a ~20 % margin of error. In the case of a forward slash line (/) the number indicates discharge before and after regulation, respectively.

(g) Drainage basin is the main drainage basin to which the site belongs. Norway is divided into 262 main drainage basins/catchment areas.

(h) The traditional regions of Norway are: <u>Eastern Norway (EN)</u>; Østfold, Akershus, Oslo, Hedmark, Oppland, Buskerud, Vestfold and Telemark. <u>Southern Norway (SN);</u> Aust- and Vest-Agder. <u>Western Norway (WN);</u> Rogaland; Hordaland, Sogn og Fjordane and Møre og Romsdal. <u>Trøndelag (TR)</u>: Sør- and Nord-Trøndelag. <u>Northern Norway (NN)</u>; Nordland, Troms and Finnmark.

There is some uncertainty regarding the accuracy of the years when the regulation was completed. Ideally the year should reflected when the regulation was finalized and affected the natural flow of water, but that somewhat difficult to find. The NVE-database only contained information on when the license was granted. In most cases however, the actual regulation took take place some years after that.

Appendix B – Normality test results

Results of the Anderson-Darling test for normality. Significant results (α = 0.01) are in bold.

		Station number	Station name	Freeze-up			Break-up			Ice cover duration		
				AD-statistic	p-value	Comment	AD-statistic	p-value	Comment	AD-statistic	p-value	Comment
Lake sites	Regulated	2.375.1	Aursjø	0.385	0.379	OK	0.460	0.249	OK	0.340	0.481	OK
		12.127	Bergsjø	0.808	0.034	OK	0.293	0.588	OK	0.577	0.127	OK
		2.162	Bygdin	0.171	0.927	OK	0.724	0.055	SCX	0.263	0.683	OK
		2.167	Vinsteren	0.595	0.117	OK	0.695	0.066	SS	0.347	0.467	OK
		2.15	Breiddalsvatn	0.338	0.492	OK	0.240	0.767	OK	0.532	0.167	OK
		2.79	Tessevatn	0.432	0.296	OK	1.260	**<0.005**	SCX	0.510	0.189	OK
		15.9	Tunhovdfjord	0.645	0.089	SS	1.262	**<0.005**	SCX	0.543	0.158	OK
		2.111	Aursunden	1.098	**0.007**	S	0.611	0.109	OK	0.736	0.054	OK
		12.87	Øyangen	0.797	0.037	SC	0.387	0.380	OK	0.286	0.613	OK
		139.5	Namsvatn	0.257	0.709	OK	0.968	0.014	S	0.309	0.548	OK
		2.82	Osensjøen	0.772	0.041	SC	0.408	0.332	OK	0.398	0.352	OK
		12.89	Volbufjord	1.231	**<0.005**	SC	0.235	0.782	OK	0.893	0.021	SS
		2.132	Lomnessjø	1.398	**<0.005**	C	0.498	0.204	OK	0.935	0.016	SCX
		2.14	Storsjø	1.015	0.011	SC	2.906	**<0.005**	CX	2.113	**<0.005**	CX
		23.2	Færåsen	0.820	0.032	SC	2.890	**<0.005**	SCX	0.796	0.036	SCX
		77.2	Veitastrondsvatn	1.991	**<0.005**	C	1.745	**<0.005**	CX	2.076	**<0.005**	CX
		16.32	Hjartsjø	1.498	**<0.005**	C	1.427	**<0.005**	SCX	0.904	0.020	CX
		12.98	Krøderen	0.836	0.029	SC	0.237	0.778	OK	0.752	0.048	SS
		2.825.39	Mjøsa (Kise-Kapp)									
		72.7	Vassbygdvatn	0.652	0.085	SC	3.511	**<0.005**	CX	0.548	0.153	SCX
		62.5	Bulken (Vangsvatnet)	1.832	**<0.005**	C	5.028	**<0.005**	CX	1.203	**<0.005**	CX
	Unregulated	2.131	Atnsjø	0.433	0.295	OK	0.457	0.257	OK	0.496	0.206	OK
		311.4	Femundsenden	0.267	0.678	OK	0.335	0.503	OK	0.316	0.534	OK
		311.7	Engeren	0.358	0.444	OK	0.339	0.492	OK	0.255	0.717	OK
		80.1	Rørvikvatn	1.159	**<0.005**	C	0.406	0.338	OK	0.796	0.036	SCX
		307.5	Murusjø	0.599	0.115	OK	0.326	0.513	OK	0.634	0.092	SCX
		24.13.13	Lygne (sørenden)	1.739	**<0.005**	C	3.608	**<0.005**	CX	2.037	**<0.005**	CX

		83.2	Hestadfjorden	1.071	**0.008**	SC	4.390	**<0.005**	CX	1.883	**<0.005**	CX
		314.3	Rømsjø	0.303	0.562	OK	3.883	**<0.005**	CX	0.872	0.023	SCX
		82.1	Nautsundvatn	1.113	**0.006**	SC	2.096	**<0.005**	CX	0.504	0.196	OK
		167.3	Kobbvatn	0.592	0.119	SC	0.405	0.375	OK	0.940	0.016	SCX
River sites	Regulated	26.5	Dorgefoss	–	–	–	3.064	**<0.005**	CX	–	–	–
		73.1	Lo Bru	0.564	0.138	SC	1.497	**<0.005**	One value	0.366	0.421	OK
		2.117	Stai	0.498	0.204	SC	0.526	0.174	OK	1.107	**0.006**	SCX
		2.2	Nor	0.329	0.511	OK	0.415	0.328	OK	0.296	0.587	OK
		122.2	Haga Bru	0.782	0.041	SC	0.645	0.089	SCX	0.837	0.029	SCX
		103.4	Horgheim	0.470	0.241	OK	1.551	**<0.005**	CX	0.697	0.066	SCX
		22.4	Kjølemo	0.435	0.291	OK	0.400	0.353	OK	0.448	0.269	OK
		246.1	Bjørnvatn	0.374	0.404	OK	0.317	0.529	OK	0.275	0.646	OK
		15.18	Bommestad bru	1.064	**0.008**	C	0.455	0.259	OK	0.477	0.228	OK
	Unregulated	2.130	Atna Bru	0.463	0.249	OK	0.207	0.861	OK	0.313	0.540	OK
		12.70	Etna	1.118	**0.006**	SC	0.463	0.250	OK	0.324	0.518	OK
		311.6	Nybergsund	0.902	0.020	SC	0.468	0.242	OK	0.433	0.293	OK
		22.5	Austerhus	0.713	0.058	SS	0.528	0.166	OK	0.576	0.125	SCX
		15.20	Jondalselv	0.450	0.268	OK	1.011	0.011	SCX	0.233	0.791	OK
		196.35	Malangsfoss	2.367	**<0.005**	C	0.190	0.895	OK	1.477	**<0.005**	CX
		212.2	Stengelsen	0.731	0.054	SC	0.517	0.182	OK	0.502	0.198	OK
		234.1	Polmak	0.576	0.130	SC	0.305	0.562	OK	0.212	0.850	OK

Notes:

C: Concave, SC: Slightly concave, CX: Convex, SCX: Slightly convex, S: S-shaped, SS: Slightly S-shaped, One value indicates that one value is the cause of the non-normality.

Bow shaped probability plots indicates that the data have excessive skewness (i.e. they are not symmetrically distributed). A concave pattern will indicate that the data is right skewing. A convex pattern is apparent when the data is left skewing. An S-shaped pattern indicates that the data have excessive kurtosis.

Appendix C – Completeness of ice records

Data completeness post quality control with removal of erroneous values. Values in bold indicate that the records is missing more than 15 % of the data, and hence/thus were excluded from the subsequent analyses. The freeze-up serie of Dorgefoss was too short to perform a satisfactory analysis.

				Data completeness*		
		Station number	Station name	Freeze–up	Break–up	Ice cover duration
Lake stations	Regulated	2.375.1	Aursjø	100 %	100 %	100 %
		12.127	Bergsjø	98 %	100 %	100 %
		2.162	Bygdin	98 %	98 %	95 %
		2.167	Vinsteren	98 %	90 %	90 %
		2.15	Breiddalsvatn	100 %	97 %	97 %
		2.79	Tessevatn	90 %	90 %	88 %
		15.9	Tunhovdfjord	96 %	91 %	89 %
		2.111	Aursunden	98 %	97 %	96 %
		12.87	Øyangen	94 %	100 %	94 %
		139.5	Namsvatn	97 %	95 %	95 %
		2.82	Osensjøen	95 %	95 %	95 %
		12.89	Volbufjord	100 %	100 %	100 %
		2.132	Lomnessjø	100 %	**84 %**	93 %
		2.14	Storsjø	94 %	92 %	90 %
		23.2	Færåsen	100 %	98 %	98 %
		77.2	Veitastrondsvatn	85 %	93 %	**81 %**
		16.32	Hjartsjø	89 %	93 %	85 %
		12.98	Krøderen	97 %	98 %	97 %
		2.825.39	Mjøsa (Kise-Kapp)	93 %	95 %	93 %
		72.7	Vassbygdvatn	94 %	95 %	92 %
		62.5	Bulken (Vangsvatnet)	88 %	92 %	86 %
	Unregulated	2.131	Atnsjø	94 %	98 %	98 %
		311.4	Femundsenden	99 %	98 %	96 %
		311.7	Engeren	97 %	96 %	93 %
		80.1	Rørvikvatn	100 %	100 %	100 %
		307.5	Murusjø	92 %	84 %	87 %
		24.13.13	Lygne (sørenden)	88 %	87 %	**83 %**
		83.2	Hestadfjorden	96 %	86 %	88 %
		314.3	Rømsjø	94 %	92 %	100 %
		82.1	Nautsundvatn	96 %	95 %	95 %
		167.3	Kobbvatn	97 %	98 %	97 %
Ri	Re	26.5	Dorgefoss		90 %	
		73.1	Lo Bru	92 %	96 %	94 %

	22.4	Kjølemo	100 %	97 %	97 %
	2.117	Stai	98 %	99 %	98 %
	2.2	Nor	100 %	99 %	99 %
	122.2	Haga Bru	98 %	93 %	92 %
	103.4	Horgheim	**80 %**	87 %	**75 %**
	246.1	Bjørnvatn	96 %	98 %	96 %
	15.18	Bommestad bru	100 %	97 %	100 %
Unregulated	2.130	Atna Bru	95 %	92 %	92 %
	12.70	Etna	99 %	95 %	93 %
	311.6	Nybergsund	100 %	91 %	95 %
	15.20	Austerhus	97 %	95 %	92 %
	22.5	Jondalselv	93 %	100 %	93 %
	196.35	Malangsfoss	95 %	100 %	97 %
	212.2	Stengelsen	93 %	97 %	93 %
	234.1	Polmak	97 %	98 %	95 %

* It might seem counterintuitive that ice cover duration can be more complete than freeze-up or break-up. The explanation for this is that the two/three does not necessarily represent the same period, i.e. ice cover duration could be a shorter period than the two former.

Appendix D – Results of the homogeneity tests

Table 1: Summary of the results of absolute homogeneity tests applied to all variables. Ordered by variable and station type (lake or river).

Variable	Station type	Class 1 "useful"	Class 2 "doubtful"	Class 3 "suspect"
	Lake sites	27 (87 %)	1 (3 %)	3 (10 %)
Freeze-up	River sites	11 (73 %)	1 (7 %)	3 (20 %)
	All sites	38 (83 %)	2 (4 %)	6 (13 %)
	Lake sites	24 (80 %)	2 (7 %)	4 (13 %)
Break-up	River sites	14 (82 %)	1 (6 %)	2 (12 %)
	All sites	38 (81 %)	3 (6 %)	6 (13 %)
	Lake sites	25 (86 %)	2 (7 %)	2 (7 %)
Ice cover duration	River sites	11 (73 %)	1 (7 %)	3 (20 %)
	All sites	36 (82 %)	3 (7 %)	5 (11 %)

Table 2: Summary of the results of absolute homogeneity tests applied to all variables. Ordered by variable and whether or not the sites have been affected by regulations.

Variable	Affected by regulation	Class 1 "useful"	Class 2 "doubtful"	Class 3 "suspect"
Freeze-up	No	15 (83 %)	1 (6 %)	2 (12 %)
	Yes	23 (82 %)	1 (4 %)	4 (14 %)
Break-up	No	15 (83 %)	2 (11 %)	1 (6 %)
	Yes	23 (79 %)	1 (3 %)	5 (17 %)
Ice cover duration	No	14 (82 %)	0 (0 %)	3 (18 %)
	Yes	21 (78 %)	3 (11 %)	3 (11 %)

Table 3: Results of absolute homogeneity test applied to all variables. Absolute test results were classified as "useful", "doubtful" or "suspect" based on the criterions put forward in section 4.2.1. A hyphen (—) indicate that the records were removed from the analysis prior to homogeneity testing due to a large percentage of missing values (> 15 %).

				Homogeneity assessment		
		Station number	Station name	Freeze–up (FU)	Break–up (BU)	Ice cover duration (ICD)
Lake stations	Regulated	2.375.1	Aursjø	Useful	Useful	Useful
		12.127	Bergsjø	Useful	Useful	Useful
		2.162	Bygdin	Useful	Useful	Useful
		2.167	Vinsteren	Useful	Useful	Useful
		2.15	Breiddalsvatn	Useful	Useful	Useful
		2.79	Tessevatn[1]	Useful	Suspect	Doubtful
		15.9	Tunhovdfjord	Useful	Useful	Useful
		2.111	Aursunden[2]	Suspect	Suspect	Suspect

		12.87	Øyangen	Useful	Useful	Useful
		139.5	Namsvatn[3]	Doubtful	Useful	Useful
		2.82	Osensjøen[4]	Useful	Suspect	Useful
		12.89	Volbufjord	Useful	Useful	Useful
		2.132	Lomnessjø[5]	Useful	—	Doubtful
		2.14	Storsjø[6]	Useful	Suspect	Useful
		23.2	Færåsen (Eptevatn)	Useful	Useful	Useful
		77.2	Veitastrondsvatn[7]	Useful	Doubtful	—
		16.32	Hjartsjø	Useful	Useful	Useful
		12.98	Krøderen[8]	Suspect	Useful	Suspect
		2.825.39	Mjøsa (Kise-Kapp)	Useful	Useful	Useful
		72.7	Vassbygdvatn	Useful	Useful	Useful
		62.5	Bulken (Vangsvatnet)	Useful	Useful	Useful
	Unregulated	2.131	Atnsjø	Useful	Useful	Useful
		311.4	Femundsenden[9]	Suspect	Useful	Suspect
		311.7	Engeren	Useful	Useful	Useful
		80.1	Rørvikvatn	Useful	Useful	Useful
		307.5	Murusjø	Useful	Useful	Useful
		24.13.13	Lygne (sørenden)[10]	Useful	Doubtful	—
		83.2	Hestadfjorden	Useful	Useful	Useful
		314.3	Rømsjø	Useful	Useful	Useful
		82.1	Nautsundvatn	Useful	Useful	Useful
		167.3	Kobbvatn	Useful	Useful	Useful
River stations	Regulated	26.5	Dorgefoss	—	Useful	—
		73.1	Lo Bru[11]	Suspect	Useful	Useful
		2.117	Stai[12]	Useful	Suspect	Doubtful
		2.2	Nor	Useful	Useful	Useful
		122.2	Haga Bru	Useful	Useful	Useful
		103.4	Horgheim	—	Useful	—
		22.4	Kjølemo	Useful	Useful	Useful
		246.1	Bjørnvatn[13]	Suspect	Useful	Suspect
		15.18	Bommestad bru	Useful	Useful	Useful
	Unregulated	2.130	Atna Bru[14]	Doubtful	Suspect	Suspect
		12.70	Etna[15]	Useful	Doubtful	Useful
		311.6	Nybergsund	Useful	Useful	Useful
		22.5	Austerhus	Useful	Useful	Useful
		15.20	Jondalselv	Useful	Useful	Useful
		196.35	Malangsfoss[16]	Suspect	Useful	Suspect
		212.2	Stengelsen	Useful	Useful	Useful
		234.1	Polmak	Useful	Useful	Useful

Notes:

[1] The parametric tests detected breaks in BU and ICD in 1955 (SNHT and Buishand) and 1999 (Buishand), respectively, while the Pettitt test did not detect any breaks. The breaks could not be explained by available metadata, i.e. the lake was regulated in 1942, with an additional regulation in 1963 (transfer of water from a nearby catchment of River Veo). The AD-test showed that the BU records is/was clearly non-normal ($p < 0.005$). Hence, it is not impossible the breaks were in incorrectly detected by the parametric tests.

[2] All tests detected breaks in FU, BU and ICD. The location specific tests indicated that the breaks occurred in 1935, 1962 and 1935, respectively. Available metadata showed that Aursunden was regulated in 1923/24 (between 691 and 685 MASL). Hence, the detected breaks could not be explained with/be the regulation of the lake. The data period after 1935 for freeze-up and ice cover duration and 1962 for break-up appeared to be OK.

[3] Both the Pettitt test and the SNHT detected a break in FU in 1949. Metadata showed that Namsvatn was regulated in 1948/49. The regulated resulted in a 14 m increase in water level, more than doubling the average depth and volume of lake. It appears reasonable that the regulation could have a homogeneity break in the freeze-up dates, i.e. later ice formation.

[4] All tests except the Buishand range test detected breaks in BU. The Pettitt test identified 1989 as the year of break, while the SNHT located the break in 2003. No explanation could be found in the relatively scant metadata, which only contains information on regulations.

[5] Both the Buishand range test and the Von Neumann ratio test detected a break in ICD. The Buishand range test identified 1939 as the year of break. No explanation could be found in the metadata.

[6] All tests detected a break in BU. The location specific tests indicated that the break occurred in 1986/87. No explanation could be found in the metadata.

[7] Both the SNHT and the Von Neumann ratio test detected a break in BU. The SNHT identified 1988 as the year of break. No explanation could be found in the metadata. However, the AD-test showed that BU were clearly ($p < 0.005$) non-normal. Hence, it is not impossible the break were in incorrectly detected by the parametric tests.

[8] All tests detected breaks in FU and ICD. The location specific tests indicated that the break occurred in 1924/1926 for freeze-up and 1925 for ice cover duration. Metadata showed that Krøderen was regulated in 1961 (between 133 and 131 MASL). Hence, the detected breaks could not be explained with/be the regulation of the lake. The data period after ~1925 appeared to be OK for both parameters. BU was OK for the entire data period.

[9] All tests detected breaks in FU and ICD. The location specific tests indicated that the break occurred in 1946 (1963) for freeze-up and 1963 for ice cover duration. Metadata showed that Femunden was (is) not regulated. Hence, the breaks could not be explained with regulation of the lake. The data period after 1946 for freeze-up and 1963 for ice cover duration appeared to be OK. BU was OK for the entire data period.

[10] The Buishand range test and the Von Neumann ratio test detected a break in BU. The Buishand range test identified 1988 as the year of break. Metadata showed that Lygne was (is) not regulated. Hence, the breaks could not be explained with regulation of the lake. The AD-test showed that the BU records was clearly non-normal ($p < 0.005$). Hence, it is not impossible the breaks were in incorrectly detected by the parametric tests.

[11] All tests detected a break in FU. The location specific tests indicated that the break occurred in 1952. Metadata showed that the river was regulated in 1971 – 74. Hence, the detected breaks could not be explained with the regulation of the river.

[12] All tests detected a break in BU, while two tests (SNHT and Von Neumann) detected a break in ICD. The location specific tests indicated that the break occurred in 1936 (1918) for break-up and 1917 for ice cover duration. The AD-test showed that the ICD records were clearly non-normal ($p = 0.006$). Hence, it is not impossible the breaks ICD were in incorrectly detected by the parametric tests. Metadata showed that Glomma upstream Stai had been regulated twice: In 1923/24 by damming of Aursunden which caused substantially increased winter discharges; by transfer of water to the neighboring Rendalen valley in 1971/72. The latter drastically reduced the winter discharge.

[13] All tests except the Buishand range test detected breaks in FU and ICD. The location specific tests indicated that the breaks occurred in 1929 for freeze-up and 1929/33 for ice cover duration. Pasvikelva originates in Lake Inari (in Finland), which has been regulated since the 1940s. Hence, the detected breaks could not be explained with the regulation of the river.

[14] All tests detected breaks in BU and ICD, while two tests (Pettitt and Von Neumann) detected breaks in FU. The location specific tests indicated that the breaks occurred in 1937 for break-up and ice cover duration and in 1953 for freeze-up. Metadata showed that the Atna River was (is) not regulated. Hence, the breaks could not be explained with regulation of the river.

[15] The SNHT and the Von Neumann ratio test detected a break in BU. The SNHT identified 1933 as the year of break. Metadata showed that the Etna River is not regulated. Hence, the breaks could not be explained with regulation of the river.

[16] All tests detected breaks in FU and ICD. The location specific tests indicated that the breaks occurred in 1953/54 for freeze-up and 1953/56 for ice cover duration. Metadata showed that the river was regulated in 1972. Hence, the breaks could not be explained with regulation of the river.